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Influence of Aggregate Gradation and Particle Shape/Texture on Permanent Deformation of Hot Mix Asphalt Pavements

by Randolph C. Ahlrich

WES

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Prepared for U.S. Department of Transportation,
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Final report

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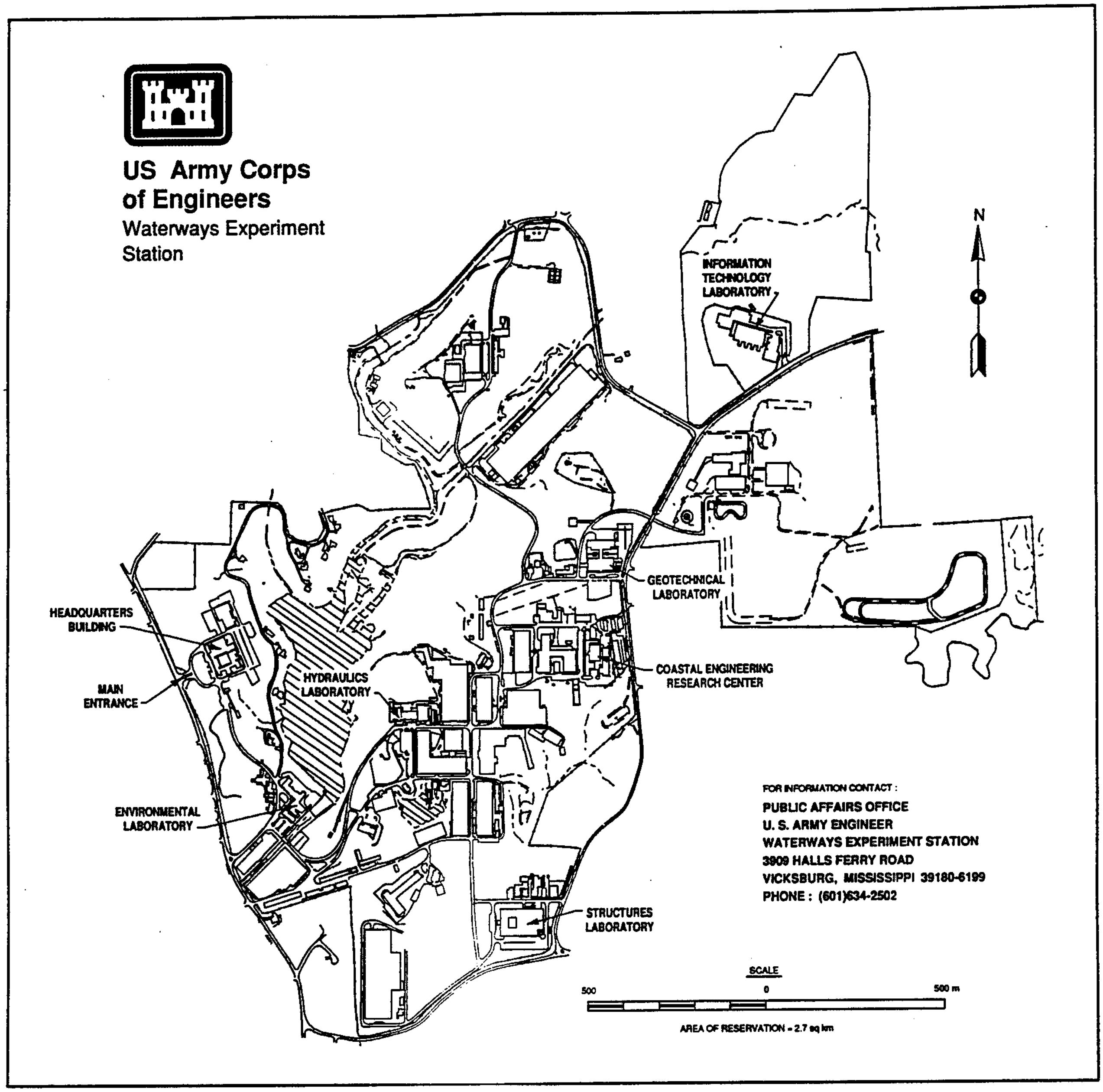

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PREFACE

This study was conducted by the Airfields and Pavements Division (APD), Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for the U.S. Department of Transportation, Federal Aviation Administration (FAA), under Inter-Agency Agreement No. DTFA01-90-Z-02069, "Durability Criteria for Airport Pavements." This study was conducted from October 1990 to August 1994. Dr. Xiagong Lee was the FAA Technical Monitor.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL, and Dr. G. M. Hammitt II, Chief, APD. This report was prepared under the direct supervision of Mr. T. W. Vollor, Chief, Materials Analysis Branch, APD. APD personnel engaged in the laboratory and field testing included Messrs. Bill Burke, Jerry Duncan, Roosevelt Felix, Herbert McKnight, and Joey Simmons. Instrumentation Services Division support was provided by Mr. Tommy Carr and Ms. August Williams. The project's Principal Investigator and author of this report was Dr. Randy C. Ahlrich. This report was also submitted to and accepted by the Graduate School at Auburn University as Dr. Ahlrich's dissertation.

Director for WES during the preparation and publication of this report was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

CONVERSION FACTORS, NON-SI TO SI UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI units as follows:

Conversion Factors, Non-SI to SI Units of Measurement		
Multiply	**By**	**To Obtain**
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	meters
inches	2.54	centimeters
gallons	3.785412	cubic decimeters
pounds (force)	4.448222	newtons
pounds (mass) per square yard	0.542492	kilograms per square meter
quarts (U.S. liquid)	0.9463529	cubic decimeters
square feet	0.09290304	square meters
square yards	0.8361274	square meters
tons (2,000 pounds, mass)	907.1847	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F-32). To obtain Kelvin (K) readings, use: K = (5/9)(F-32) + 273.15.

CHAPTER I INTRODUCTION

BACKGROUND

In recent years, many hot mix asphalt (HMA) pavements have experienced premature rutting. Rutting is defined as permanent deflection of the pavement surface that develops in the wheelpaths under channelized traffic due to permanent deformation in the top 3 to 4 in. of HMA. The apparent increase in HMA pavement rutting has been due to higher traffic volumes, increased loads and tire pressures, poor construction quality control, and decreased quality of HMA mixtures. (1,2,3)

Since approximately 85 percent of the total volume of HMA mixtures consists of aggregates, the performance of HMA mixtures is greatly affected and influenced by the properties of the aggregate blend. The aggregate properties that significantly influence the performance of HMA mixtures are gradation, shape (angularity) and texture (roughness). The quality of a HMA mixture is influenced by the shape of the aggregate gradation because gradation controls the matrix void structure. A very dense gradation (maximum density line) theoretically produces the strongest HMA mixtures, but because of low aggregate voids, this mixture is very sensitive and changes significantly with small variations in asphalt content. The shape and texture of coarse (plus No. 4 sieve) and fine (minus No. 4 sieve) aggregates control the mixture's strength and rut resistance thus affecting performance and serviceability. Rough angular aggregates produce higher quality pavements than smooth uncrushed aggregates. (4)

Current state and federal specifications for aggregate properties in HMA pavements are primarily based on experience and empirical characterization tests. These specifications require that the composite aggregate blend fall within a specified gradation band, have a minimum requirement for percent crushed (fractured) faces for coarse and fine aggregate fractions, and have limitations on the amount of natural sand (naturally occurring fine aggregate) materials. Although high quality HMA pavements have been constructed with these requirements, these aggregate properties are empirical and are not performance-related tests.

In the future, traffic volumes and loads will increase, so proper selection and evaluation of aggregate properties for HMA pavements will be required to insure high quality HMA pavements that resist permanent deformation. Quantification of aggregate properties with rational characterization test methods that are performance-related are desirable.

OBJECTIVES

The research described in this report was conducted and analyzed to achieve the following objectives:

1. To evaluate the influence of aggregate gradation and particle shape and texture on permanent deformation characteristics of HMA mixtures.

2. To characterize and quantify aggregate shape and texture with performance-related aggregate tests.

3. To develop relationships between physical properties of aggregates and the permanent deformation characteristics of HMA mixtures.

4. To evaluate the benefits of asphalt modification on permanent deformation characteristics of HMA mixtures with substandard aggregate properties.

5. To validate confined repeated load deformation (triaxial creep) test by evaluating field samples trafficked with aircraft loads and tire pressures.

SCOPE

The scope of this research study included a review of existing data and available literature, a laboratory evaluation to characterize aggregate properties and HMA mixtures, an evaluation of field test items, and an analysis of the data. The research study consisted of the following phases:

1. Selection and fabrication of aggregate blends.
2. Characterization of aggregate properties.
3. Evaluation of AC-20 HMA mixtures.
4. Evaluation of modified AC-20 HMA mixtures.
5. Construction, trafficking, and evaluation of field test section.
6. Confined repeated load deformation testing of field cores.
7. Data analyses.

The focus of the research was to investigate and determine the effects of aggregate gradation and particle shape and texture on permanent deformation properties of HMA mixtures.

Eighteen aggregate blends were selected to evaluate the effects of the shape of the aggregate gradation curve and the particle shape and texture of the aggregates on HMA mixtures. Each aggregate blend was separated on the No. 4 sieve to allow characterization of the coarse and fine aggregate fractions. The coarse aggregate fraction was tested with the percent crushed particle method (CRD-C-171), Particle Index test (ASTM D 3398), modified NAA particle shape and texture method, and the unit weight and voids in aggregate test (ASTM C 29). The fine aggregate fraction was tested with the percent crushed particles method, Particle Index test, NAA particle shape and texture method, and direct shear method. Details of these test procedures are presented in Chapter IV.

Following the aggregate characterization tests, a volumetric mix design was conducted on all eighteen test aggregate gradation blends with an AC-20 binder. All HMA mixtures were compacted with the Corps of Engineers Gyratory Testing Machine (GTM) using 200 psi vertical pressure, 1-degree gyration angle, and 30 revolutions which is equivalent to a 75-blow Marshall hand hammer compactive effort. An optimum asphalt content was selected at 4 percent air voids for each HMA mixture. These HMA specimens were tested with the Marshall stability and flow, indirect tensile, direct shear, and confined repeated load deformation tests. Details of these procedures are presented in Chapter IV.

Two polymer modified AC-20 binders were mixed with eight selected aggregate blends to determine the benefits of asphalt modification. The asphalt modifiers were a SBS (styrene-butadiene-styrene) and a LDPE (low density polyethylene). A Marshall mix design was conducted for each modified HMA mixture to select an optimum asphalt content at 4 percent air voids. The same gyratory compactive effort and HMA mixture tests were conducted on the modified HMA mixtures that were conducted on the AC-20 HMA mixtures.

After completion of the laboratory evaluation, ten test items that included seven aggregate gradations and aggregate blends with various particle shapes and textures were constructed, trafficked, and evaluated. The trafficking was accomplished with a load cart assembly simulating aircraft loads (40,000 pounds) and tire pressures (200 psi). Rut depth measurements were determined at various traffic levels and after 12,000 passes of the load cart assembly.

REPORT FORMAT

This report provides detailed discussion describing the research project, test results and data analyses from laboratory and field evaluations, conclusions, and recommendations. Chapter II provides a literature review on the effects of aggregate properties on pavement rutting and summarizes aggregate property and HMA mixture characterization tests used in previous research studies. The research experimental plan is outlined in detail in Chapter III. The laboratory materials and test methods used to characterize and evaluate the aggregate and HMA mixtures are discussed in Chapter IV. Chapter V presents the test results and analyses for the laboratory evaluations that includes aggregate characterization and AC-20 and modified AC-20 HMA mixture evaluations. The description of the test section and discussion of the test results from the field evaluation are presented in Chapter VI. Development of rutting models is presented in Chapter VII. Conclusions and recommendations derived from this study are presented in Chapter VIII.

CHAPTER II REVIEW OF LITERATURE

TYPES AND CAUSES OF RUTTING

Rutting in HMA pavements develops in the wheelpaths under channelized traffic. It is caused by permanent deformation of materials in the pavement structure under repeated loads. Permanent deformation in HMA layers is a result of two processes: (2,4,5)

1. Densification - a consolidation or depression of HMA layers beneath tire loads. This type of permanent deformation is caused by poor compaction during construction of the HMA layers or an inadequate mix design.

2. Plastic flow - a consolidation or depression in the HMA layers accompanied by upheaval on either side of the depression. HMA mixtures that exhibit plastic flow are generally caused by an unstable tender mixture.

The two types of permanent deformation are illustrated in Figure 1.

This report primarily addresses issues related to permanent deformation caused by densification and plastic flow. These two types of permanent deformation are basically controlled by the quality of the aggregates and the HMA mix designs. Some common deficiencies that have been identified as causes of permanent deformation are: (2,5)

1. Improper aggregate gradation.
2. Excessive asphalt content.
3. Excessive use of rounded aggregate.

4. Insufficient field compaction.

5. Inadequate quality control.

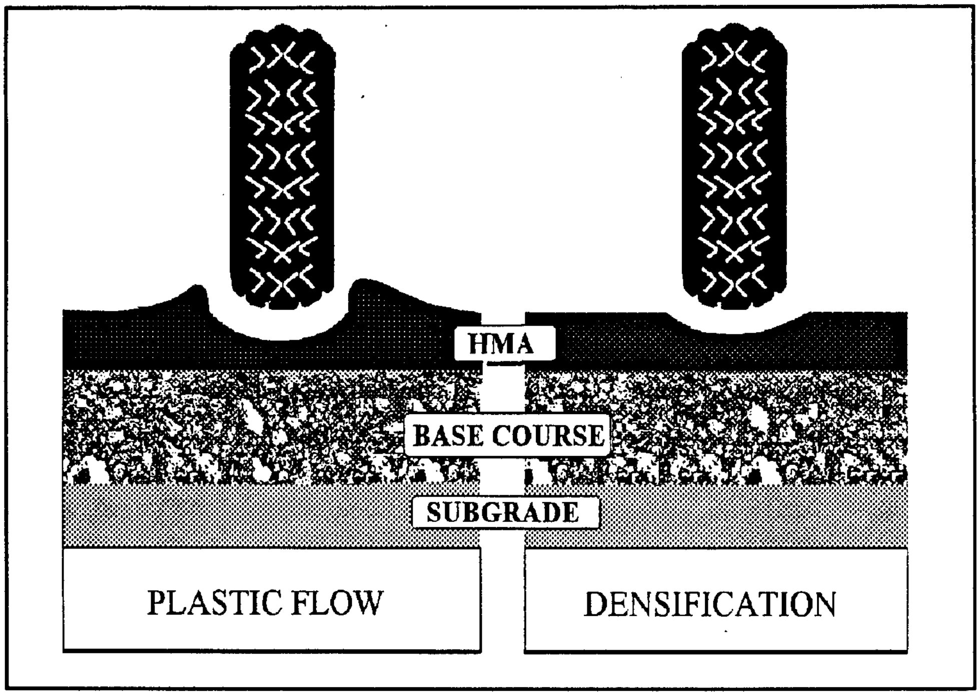


Figure 1. Types of Permanent Deformation in HMA Pavement

EFFECTS OF AGGREGATE PROPERTIES ON HMA MIXTURES

Much research has been conducted concerning the effects of aggregate properties and characteristics on the quality and performance of HMA mixtures. A review of this research has been conducted and summarized into general categories that best relates aggregate properties to the performance of HMA mixtures. The literature review has been divided into the following areas: (1) laboratory evaluations, and (2) field investigations.

Laboratory Evaluations

Elliot, Ford, Ghanim and Tu (6) conducted an investigation to evaluate the effect of variations in aggregate gradation on the properties of HMA mixtures. The primary objectives were to determine the effect of gradation variation on (1) creep behavior as a measure of rutting resistance, (2) split tensile strength as an indicator of fatigue resistance potential, (3) Marshall mix properties as a measure of mix acceptability and (4) resilient modulus as a design parameter. The authors evaluated five aggregate gradations of crushed limestone that simulated typical Arkansas State Highway and Transportation Department (AHTD) HMA mixtures. These gradations represented the extreme variations (based on field extractions) encountered on AHTD paving projects. The aggregate blends included the standard 3/4 in. maximum aggregate AHTD gradation (mid band), a coarse gradation (standard blend minus maximum variations for each sieve), a fine gradation (standard blend plus maximum variations for each sieve), and two poorly-graded (cross-over) gradations. The poorly-graded gradations varied from the coarse gradation values to the fine gradation values (coarse-fine) and from the fine gradation values to the coarse gradation values (fine-coarse) and crossed over at the No. 4 sieve.

From this investigation, the authors concluded the following:

1. Variations in gradation have the greatest effect when the gradation changes the general shape of the gradation curve (poorly-graded or cross-over gradations).

2. Creep stiffness is lowest for poorly-graded, cross-over gradations.

3. Coarse gradation produced the lowest tensile strengths.

4. Marshall stability is affected by gradation variations, fine gradation produced the highest stability while the fine-coarse poorly-graded gradation produced the lowest Marshall stability.

Marker (7) and Crawford (8) concluded that particle shape and the amount of material passing the No. 4 sieve were major factors contributing to the tenderness of an asphalt concrete mixture. They discovered that most tender pavements have an excess of middle-sized sand particles (No. 8 to No. 100) in the aggregate gradation. This excess of mid-sized sand particles is revealed as a hump in the curve when the gradation is plotted as percent passing versus the sieve size raised to the 0.45 power (Fuller curve). (9) Tenderness is generally most critical when this hump is near the No. 30 sieve. This condition is generally accompanied by a relatively low amount of minus No. 200 material. These authors also stated that rounded, uncrushed aggregates are more likely to contribute to tender mixtures, especially as the amount of uncrushed material passing the No. 4 sieve increases.

Moore and Welke (10) conducted numerous asphalt mix designs to determine the effect of fine aggregate. They stated that the asphalt concrete mixture gradation and aggregate angularity were very significant in increasing the stability of mixtures. They reported that as the mixture gradation approached the Fuller curve for maximum density, the Marshall stability increased. They also stated that the more angular the fine aggregate, the higher the stability. The study concluded that rounded fine aggregates (natural sands) produced lower stabilities than crushed fine aggregates.

Brown and Basset (11) conducted a laboratory study to determine the relationship between asphalt mixture properties and maximum aggregate size. The laboratory testing procedures were chosen to analyze the effects of varying the size of the largest aggregate in a gradation. The tests used to evaluate the various mixtures included Marshall stability and flow, indirect tensile, static creep and resilient modulus. The laboratory evaluation provided the following conclusions: (1) no connection between stability and rutting resistance,

(2) poor relationship between Marshall stability and the maximum aggregate size, (3) very little change in indirect tensile strength as maximum aggregate size changed, (4) creep test indicated increased aggregate size would be more resistant to permanent deformation, and (5) the resilient modulus indicated good correlation with maximum aggregate size (i.e., the resilient modulus value increased as the maximum aggregate size increased).

Brown, McRae and Crawley (12) gathered information from various laboratory and field studies to evaluate the effect of mineral filler, maximum aggregate size, aggregate gradation, crushed particles and stripping tendencies on the performance of asphalt concrete. The authors concluded that the quality and amount of filler greatly affected the asphalt concrete performance. They also concluded that additional minus No. 200 material produced a lower optimum asphalt content, a higher stability and a very sensitive asphalt mixture. Furthermore, some filler is required for stability, but an excessive amount (greater than 6 percent) produced unsatisfactory mixtures. The authors also stated that the maximum aggregate size greatly affected the pavement performance and that larger maximum aggregate sizes produce higher stability, better skid resistance, and lower optimum asphalt contents. The authors also stated that uncrushed aggregates such as sands and gravels produce mixtures with lower stability and decreased pavement performance.

Kim et al. (13) conducted a laboratory study to investigate the effects of aggregate type and gradation on the fatigue and permanent deformation of HMA mixtures. Diametral fatigue and uniaxial incremental static creep tests were performed on HMA specimens. The results of these tests indicated that the aggregate type (shape) had a significant effect on fatigue resistance and permanent deformation properties. The aggregates with angular shape and rough texture produced better performance. The variations in the coarse aggregate gradations did not affect the permanent deformation properties significantly.

Krutz and Sebaaly (14) evaluated the effects of aggregate gradation on permanent deformation of HMA mixtures for the Nevada Department of Transportation. This research study evaluated four aggregate gradations using two different aggregate sources and two asphalt binders. Each gradation falls inside the current FAA specification for 1 in. maximum aggregates, and they have the same shapes that follow the upper (fine), middle, and lower (coarse) limits. The HMA specimens were tested with static and repeated load triaxial test devices to determine the permanent deformation properties of each HMA mixture. The authors concluded that the type and source of the aggregate had an effect on how the HMA mixture performed. They stated that the "best" aggregate gradation may be dependent on the type and source of aggregate. The data consistently showed for all the HMA mixtures that the coarse (bottom band) aggregate gradation performed the worst and that the finer gradations (middle and top band) produced better performing mixtures.

Herrin and Goetz (15) conducted a laboratory evaluation to determine the effect of aggregate shape on the stability of asphalt concrete mixtures. This laboratory study involved crushed and uncrushed gravel, crushed limestone for the coarse aggregate (plus No. 4), and natural sand and crushed limestone sand for the fine aggregate (minus No. 4). In their tests, the strength of the mixture, regardless of the type of coarse aggregate, increased substantially when the fine aggregate was changed from rounded sand to crushed limestone. A major finding was that the strength of the asphalt mixture was affected more by a change in fine aggregate shape than a change in the coarse aggregate shape.

Wedding and Gaynor (16) evaluated the effect of particle shape in dense graded asphalt concrete mixtures. The percentages of crushed and uncrushed coarse aggregates (plus No. 4) and the types of fine aggregate (minus No. 4) which included natural and washed concrete sands were varied in the mixtures. The analysis of the different aggregate blends was conducted on specimens produced by the Marshall procedure. The authors reached the following conclusions from this study.

1. Asphalt mixtures with crushed particles produced higher stability values than mixtures with uncrushed, rounded aggregates.

2. The use of crushed gravel sand in place of natural sand increased the stability of the mixtures as much as adding 25 percent crushed coarse aggregate.

3. The substitution of all crushed aggregate for natural sand and gravel increased the stability approximately 45 percent.

4. An increase in the amount of crushed particles caused a decrease in unit weight, and an increase in voids in mineral aggregate and optimum asphalt content.

Griffith and Kallas (17,18) conducted several laboratory evaluations that determined the effects of aggregate characteristics on asphalt mixtures. They studied the effect of aggregate type on voids and strength characteristics of asphalt concrete mixtures. The authors found that uncrushed gravel mixtures develop voids lower than crushed gravel mixtures for a given asphalt content. They also evaluated the influence of fine aggregates on the strength of asphalt concrete specimens. Various combinations of aggregate gradations using natural and crushed coarse aggregate and natural sand fine aggregate were analyzed. They found that an increase in angularity of crushed fines increased the Marshall and Hveem stability values at the optimum asphalt content. An increase in angularity in the fine aggregate also increased the void contents and increased the optimum asphalt contents.

Field (19) conducted a study to determine the effect of variation of crushed aggregate percentages in asphalt concrete mixtures. He found that replacing uncrushed aggregates with crushed aggregates increased the stability and increased the void content and voids in mineral aggregate (VMA) for a given asphalt content. The higher VMA values allow additional asphalt in the mix which improves the durability of the asphalt concrete pavement.

Gaudette and Welke (20) conducted a laboratory study that determined the effect of crushed faces on the stability of HMA mixtures. The authors evaluated the relationship between the percentage of crushed aggregate in the blend and the number of crushed faces to stability. They concluded that the stability of the mixture increased significantly when the percentage crushed aggregates was increased from 0 to 50 percent. The authors also concluded that HMA mixtures with more than 50 percent crushed aggregate in the blend produced higher stabilities with aggregates containing 3 or more fracture faces than with aggregates containing 2 or less fractured faces.

Maupin (21) conducted a laboratory study to evaluate the effect of particle shape and surface texture on the fatigue behavior of asphalt concrete. The study used three different particle shapes, round, subangular, and angular. Asphalt concrete mixtures were produced with uncrushed gravel (round), limestone (subangular), and slabby slate (angular). Beam specimens were prepared and tested with constant strain fatigue. The laboratory study concluded that rounded gravel mixture had a longer fatigue life than the other mixtures.

Shklarsky and Livneh (22) conducted a laboratory study involving sands and gravels. They evaluated the difference between uncrushed and crushed coarse aggregate combined with natural sand and crushed fine aggregate. The authors found that replacing natural sand materials with crushed fine aggregate increased the stability and strength properties of Marshall specimens, reduced permanent deformation, improved resistance to wear, reduced asphalt content sensitivity, and increased voids. They also concluded that replacing uncrushed coarse aggregate with crushed coarse aggregate did not significantly improve the asphalt concrete mixture.

Kalcheff and Tunnicliff (23) conducted a laboratory study to determine the effects of crushed aggregate size and shape on properties of asphalt concrete mixtures. They specifically evaluated the effect of coarse aggregate gradations, shape effects of fine aggregates, and effects of high mineral filler content. The laboratory specimens were produced with Marshall and Hveem methods using aggregate blends composed of natural and manufactured sands. The optimum asphalt content was approximately the same for natural sand mixtures and manufactured sand mixtures if the sands had similar particle shape. The optimum asphalt content was higher if the manufactured sand had more angular particles. The authors found that asphalt concrete mixtures containing crushed fine aggregate were more resistant to permanent deformation from repeated loadings than comparable mixtures containing natural sand. The behavior of the asphalt concrete mixture was improved when manufactured sands replaced natural sands.

Lottman and Goetz (24) evaluated the effect of crushed gravel fine aggregate on the strength of asphalt mixtures. The authors found that the strength of asphalt mixtures was increased when mixtures contained crushed gravel fine aggregate instead of natural sand fine aggregates. They stated that the increase in strength was attributed to the angularity and the roughness of the crushed fine aggregate. The authors recommended that some amount of crushed fine aggregate be used with natural sands in asphalt mixtures to produce sufficient stability for high quality pavements.

Button and Perdomo (25) conducted a study to evaluate the effects of natural sands on permanent deformation and to quantify the influence on resistance to plastic deformation when natural sand is replaced with crushed fine aggregate. The study showed that total deformation and rate of deformation increased as the percentage of natural sand increased. The shape and texture of the fine aggregate were major factors controlling plastic deformation in asphalt concrete mixtures. The authors recommended replacing natural sand material with manufactured sand to increase the resistance of the asphalt concrete pavement to permanent deformation.

Kandhal and Wegner (26) conducted a study to determine the effect of crushed aggregate on properties of asphalt concrete for the Pennsylvania Department of Transportation. They found that replacing natural sand with crushed sand improved the Marshall stability and reduced permanent deformation. The authors also concluded that replacing uncrushed coarse aggregate with crushed coarse material did not significantly improve the asphalt mix properties.

Ahlrich (27) conducted a laboratory study to determine the influence of various amounts of natural sands on the engineering properties of asphalt concrete mixtures and to set quantitative limits of natural sand to prevent the use of unstable mixtures and reduce rutting potential. The study indicated that the use of natural sand materials decreased the stability and strength characteristics of asphalt concrete mixtures and that replacing natural sand materials with crushed sand materials increased the resistance to permanent deformation. The author found that the amount of natural sand did affect the results of the indirect tensile, resilient modulus and unconfined creep-rebound tests. The indirect tensile results indicated a reduction in mixture strength as the percentage of natural sand increased. The resilient modulus test results were very inconsistent and provided no discernable trend. The unconfined creep-rebound test results indicated a strong relationship between the percentage of natural sand and rutting potential. The axial and permanent deformation values increased significantly as the natural sand content increased. The creep modulus value decreased significantly as the percentage of natural sand increased. The author concluded that to maximize the reduction in rutting potential for heavy duty pavements (airports), all aggregates should be crushed. He also stated that if natural sands were to be used, a maximum limit of 15 percent by weight should be specified.

Yeggoni, Button and Zollinger (28) conducted a research study to evaluate the influence of coarse aggregate shape and texture on permanent deformation characteristics of HMA mixtures. The study also characterized the coarse aggregate physical properties and correlated these aggregate properties to the permanent deformation characteristics of HMA mixtures. The authors concluded that the coarse aggregate fraction did influence the performance of HMA mixtures (i.e., an increase in the percentage of crushed coarse aggregate resulted in an increased Hveem stability, Marshall stability, and resistance to permanent deformation). The researchers also found a direct correlation between rutting potential of HMA mixtures and the shape of coarse aggregate particles.

Ishai and Gelber (29) conducted a laboratory study to determine the relationship between geometric irregularities of aggregates utilizing the packing volume concept developed by Tons and Geotz (30) and HMA mixture properties. The aggregate characterization test results and correlations with HMA properties indicated that this concept was valid and effectively evaluated the shape and texture of aggregates. The "pouring test" which was developed as a simple, fast, practical measurement of these geometric properties was developed by Ishai and Tons. (31) This test has recently been used in a research study by Barksdale et al. (32) to characterize aggregates and to predict rutting potential.

Boutilier (33) conducted a laboratory study to determine the relationship between the Particle Index developed by Huang (34) and the properties of asphalt concrete mixtures. The Particle Index is a function of the aggregate shape and texture. This value is larger for aggregates that are more irregular, angular and rougher. The study indicated that there was a definite relationship between the Particle Index and the properties of asphalt concrete mixtures (i.e., the Marshall stability values increased as the Particle Index values increased).

McLeod and Davidson (35) conducted an extensive laboratory study to determine the relationship between Particle Index and asphalt concrete mixtures. The authors concluded that aggregates with rounded particles and smooth surface textures have a Particle Index of 6 or 7 or less, while aggregates with highly crushed angular particles have a Particle Index of 15 to 20 or more. This study produced a distinct relationship between Particle Index and Marshall stability. They also concluded that the Particle Index of fine aggregate has a greater influence than the particle index of coarse aggregate on Marshall stability.

Meir and Elnicky (36) conducted a laboratory study to evaluate various test methods that provide information about the shape and surface texture of fine aggregates for asphalt mixtures and related these properties to asphalt concrete properties. The authors concluded that the shape and surface texture of fine aggregate could be evaluated by a number of tests. These tests include the National Crush Stone Association (now National Aggregate Association) procedure, Particle Index method, Rex and Peck Time Index, and the void ratio method of Western Technologies. The direct shear test did not produce acceptable results.

Kandhal, Motter, and Khatri (37,38) conducted a laboratory study to quantify the particle shape and texture of various natural and manufactured sands using the Particle Index test, and the National Aggregate Association's (NAA) Methods A and B. They concluded that a Particle Index value of 14 seems to be the division between natural and manufactured sands. The NAA Methods A and B also divide the natural and manufactured sands with void contents of 44.5 and 48.3 respectively.

Winford (39) conducted a laboratory study to quantify aggregate characteristics, to evaluate relationships between these characteristics and permanent deformation, and to recommend a test method for aggregate characterization. He concluded that the angle of internal friction derived from the direct shear test provides a reliable partition between natural and manufactured sands. He also concluded that a composite Particle Index value of 14 was the separation between natural and manufactured sands. NAA Methods A and B also correlated very well with the Particle Index test. He determined that the direct shear test was the simplest, quickest, and cheapest method for determining fine aggregate angularity and surface texture. The author also developed several relationships between the percentage of crushed fine aggregates and permanent strain or deformation.

Mogawer and Stuart (40,41) conducted laboratory research to evaluate test methods used to quantify sand shape and texture and the effects of sands on HMA mixture properties. These studies included the Particle Index test, the NAA method A procedure, the direct shear test, and a Michigan test method. The results of these studies indicated that the Particle Index test differentiated all poor quality sands from good quality sands at a weighted Particle Index value of 12. The NAA method A established an uncompacted void content of around 44 percent as the delineator between good and poor quality sands. The authors concluded that the direct shear test was not a good indicator of performance or aggregate shape and texture.

Jiminez (42) evaluated the Shape-Texture Index (STI) test as a method to measure shape and texture of sands. This test procedure (modified Rex and Peck) measured the flow rate (time) of minus No. 8 aggregate to determine the shape and texture characteristics (i.e., the flow time increases as the angularity and roughness of the aggregate increase). The author stated that this test procedure was economical and easy to perform and produced results that correlated very well with sand shape and texture properties.

Marks, Monroe, and Adam (43) conducted a laboratory evaluation that analyzed the effects of crushed particles in asphalt concrete mixtures. The laboratory tests included Marshall stability, indirect tensile, resilient modulus, and creep tests. Results of the study indicated stability increased substantially as the percentage of crushed aggregate increased. The resilient modulus data did not correlate with the percent of crushed particles or indicate resistance to rutting. Data from the creep test indicated rutting potential was very dependent on the percent of crushed aggregate.

Mallick, Ahlrich, and Brown (44) presented their findings on the potential of the dynamic confined creep test to predict rutting. This study involved three phases which evaluated HMA specimens at various air void contents, HMA field cores at measured rut depths, and HMA specimens produced with various percentages of crushed aggregate. The authors stated that the dynamic confined creep test can simulate field rutting and can be used to predict rutting potential of HMA mixtures. The authors also concluded that the dynamic confined creep test was successful in obtaining a significant difference in rutting potential for HMA mixtures with different amounts of crushed aggregate.

Field Investigations

Foster (45) evaluated the effect of fine aggregate on the strength of dense-graded asphalt concrete mixtures in field test sections at the U.S. Army Engineer Waterways Experiment Station (WES). The study involved constructing and trafficking test sections containing three asphalt mixtures, a sand asphalt mix and two coarse aggregate mixtures containing the same fine aggregate. Based on the pavement's performance after trafficking, the author concluded that the true capacity to resist traffic induced stresses is controlled by the characteristics of the crushed fine aggregate. These results agreed with findings from earlier tests at WES that were conducted during the development of the Marshall procedure. (46)

Grau (47) evaluated the effects of natural (uncrushed) sands and crushed fine aggregates in field test sections. This study demonstrated that increases in amounts of natural sand and fine sand gradations produced less stable mixtures. A significant decrease in stability occurred when uncrushed gravel and natural sand were used together. The stability values of asphalt concrete mixtures increased significantly when crushed fine aggregate was used in place of natural sand.

Cross and Brown (48,3) conducted a study to evaluate aggregate properties that affect pavement rutting. Samples from 42 pavements that had rutted in less than 5 years or been in service for more than 5 years without rutting were tested to determine aggregate and mixture properties. The authors concluded that aggregate properties do not significantly affect the rutting potential when in-place air voids are below 2.5 percent since the mixtures tend to rut regardless of aggregate properties. They stated that the percent fractured faces of the coarse aggregate affected the rate of rutting. The rate of rutting increased as the percent of crushed faces decreased. The authors also concluded that the rate of rutting increased as the angularity of fine aggregate decreased. They concluded that higher percentages of crushed coarse aggregate and crushed fine aggregate reduced the potential for rutting.

Parker and Brown (49) evaluated thirteen pavements for the Alabama Highway Department to determine the effects of aggregate properties on rutting susceptibility of HMA mixtures. The aggregate properties evaluated were gradation, percent crushed coarse aggregate, and particle shape and texture of fine aggregate. The correlations of aggregate properties with rutting were poor, but definite trends were indicated. The authors reported that pavements with angular crushed particles experienced less rutting than HMA pavements with uncrushed round aggregates. This study demonstrated that rutting in HMA pavements is a complicated process and is affected by multiple factors (aggregate properties, asphalt content, air voids).

Kandhal, Cross, and Brown (50) conducted a study for the Pennsylvania DOT to evaluate the rutting potential of HMA pavements under high tire pressures. The authors evaluated 34 pavements and identified material and mixture deficiencies as the controlling factors of rutting susceptibility. The authors reported that low in-place air voids were a major cause of rutting. They also stated that pavements with gravel and natural sand materials were not performing as well as pavements with crushed coarse aggregates and manufactured sands.

Ahlrich and Anderton (51) evaluated an asphalt overlay that had been constructed for a military airfield parking apron to determine the effects of aggregate properties on rutting. Immediately after being opened for traffic, the asphalt overlay exhibited significant rutting (greater than 1 in.). A laboratory recompaction analysis was conducted on samples of the in-place HMA mixture. The authors concluded that the poor performance of the asphalt concrete was due to an improperly designed and produced HMA mixture. An analysis of the extracted aggregates determined that the amount of natural sand in the in-place material was between 30 and 40 percent. These values greatly exceeded the maximum specification limit of 15 percent. The excessive amount of natural sand was determined to have been the primary cause of premature rutting.

Brown (52) conducted an investigation that evaluated pavement failures on three heliport runways in Alabama. These heliport runways had been resurfaced with 1.5 in. of HMA. Shortly after the pavement resurfacing, the helicopter landings began to damage the surface. This damage varied from scuffing the surface to gouging 1 in. deep. A laboratory analysis was conducted on pavement samples to evaluate the quality of the mixture. The analysis indicated a fine aggregate gradation with an excessive amount of natural sand (45 to 50 percent) had been used in the mixture. The author concluded that the excessive amount of natural sand was the most important factor that led to the early pavement failure.

Anderton (53) conducted an investigation to determine the causes of pavement rutting in a roadway in Colorado. In less than 2 years moderate rutting (1/2 to 3/4 in.) had occurred in the wheelpaths. Pavement samples from areas with 3/4 in. rutting and no rutting were evaluated to determine the causes of this pavement deformation. An evaluation of the aggregate in the asphalt mixtures indicated that the mixture with moderate rutting had a natural sand content of approximately 35 percent while the pavement sample with no rutting had a natural sand content of approximately 24 percent. The author concluded that excessive natural sand was the primary factor that contributed to the pavement deformation.

CHAPTER III PLAN OF STUDY

This study defines in engineering terms, the impact of aggregate properties on HMA mixtures for heavy-duty pavements. Basically, the research determined the effect of aggregate gradation and particle shape and texture on HMA strength and permanent deformation characteristics. The major emphasis of the study was to conduct aggregate characterization tests and to develop relationships between aggregate properties and the rutting potential of HMA mixtures.

This research study used the FAA specification Item P-401 (Plant Mix Bituminous Pavements) as the model for establishing aggregate gradations and blends. (54) Item P-401 requires a high quality, durable, clean, well-graded, crushed aggregate. The laboratory testing considered the effects of departures from the requirements of the specification for the standard 3/4 in. maximum aggregate size gradation, the percentage of crushed coarse aggregate particles, and the amount of natural sand material. The other standard aggregate requirements specified by Item P-401, LA Abrasion (ASTM C 131), sulfate soundness (ASTM C 88) and flat and elongated (ASTM D 4791) tests, were not examined because these tests do not correlate particularly well with pavement deformation or rutting and field performance. (55,56) Previous laboratory research and field investigations have indicated that poorly-graded aggregates, uncrushed particles, too much natural sand and excessive amounts of minus No. 200 material produce HMA mixtures that are susceptible to rutting. (6,23,25,48,49)

The aggregate sources for this laboratory evaluation included limestone, gravel (crushed and uncrushed) and natural sand materials. The limestone and crushed gravel aggregates met the requirements of Item P-401 and served as the accepted high quality aggregate. Uncrushed gravel and natural sand materials were used in conjunction with the crushed aggregates to produced the various particle shape and texture blends. The aggregates from each source were processed by screening to develop laboratory stock. All labstock aggregate materials (all sieve sizes) were evaluated to determine their gradation, absorption, and specific gravities. These processed materials were used to fabricate specific test gradations. These test gradations were selected to determine the effects of variation in aggregate gradation (shape of gradation curve), amount of crushed particles in coarse aggregate fraction (0, 30, 50, 70, 100 percent), and the amount of natural sand material in the aggregate blend (0, 10, 20, 30, 40 percent). The description and designation of the test gradations are listed in Table 1.

The test aggregate blends were selected so that the influence of aggregate gradation and particle shape and texture on rutting potential of HMA mixtures could be analyzed. The effect of the shape of the gradation curve was designed to be evaluated with Blends A-M. Blends A-H were fabricated with primarily crushed limestone materials so that the effect of gradation could be evaluated with high quality aggregates and the effect of particle shape would be minimal. Blends I-M were fabricated with crushed gravel and various amounts of natural sand to evaluate the "hump" effect in the fine aggregate (minus No. 4 sieve) portion of the gradation.

Table 1. Description of HMA Aggregate Blends

Identification	Description	Composition	Illustration
A	Center of FAA gradation band	100% crushed limestone	Figures 15 and 19
B	Coarse side (lower limit) of FAA band	92% crushed limestone 8% natural fine sand	Figures 15 and 19
C	Fine side (upper limit) of FAA band	88% crushed limestone 12% natural fine sand	Figures 15 and 19
D	Above upper limit of FAA band	91% crushed limestone 5% natural fine sand 4% natural coarse sand	Figures 15 and 19
E	Excessive No. 200 material	90% crushed limestone 8% natural fine sand 2% natural coarse sand	Figures 16 and 20
F	Poorly graded - middle	90% crushed limestone 10% natural fine sand	Figures 16 and 20
G	Poorly graded - coarse	88% crushed limestone 12% natural fine sand	Figures 16 and 20
H	Poorly graded - fine	85% crushed limestone 15% natural fine sand	Figures 16 and 20
I	Center of FAA gradation band	100% crushed gravel	Figures 17 and 21
			(Sheet 1 of 2)

Identification	Description	Composition	Illustration
J	Center of FAA band modified with 10% natural sand	90% crushed gravel 10% natural coarse sand	Figures 17 and 21
K	Center of FAA band modified with 20% natural sand	80% crushed gravel 20% natural coarse sand	Figures 17 and 21
L	Center of FAA band modified with 30% natural sand	70% crushed gravel 30% natural coarse sand	Figures 17 and 21
M	Center of FAA band modified with 40% natural sand	60% crushed gravel 40% natural coarse sand	Figures 17 and 21
N	Center of FAA gradation band	Coarse 70% crushed gravel 30% uncrushed gravel Fine 100% crushed gravel	Figures 18 and 22
O	Center of FAA gradation band	Coarse 50% crushed gravel 50% uncrushed gravel Fine 100% crushed gravel	Figures 18 and 22
P	Center of FAA gradation band	Coarse 30% crushed gravel 70% uncrushed gravel Fine 100% crushed gravel	Figures 18 and 22
Q	Center of FAA gradation band	Coarse 100% uncrushed gravel Fine 100% crushed gravel	Figures 18 and 22
R	Center of FAA gradation band	89% uncrushed gravel 6% natural fine sand 5% natural coarse sand	Figures 18 and 22

(Sheet 2 of 2)

The effects of particle shape and texture were analyzed two ways, percent crushed coarse particles and the amount of natural sand material in the aggregate blend. The effect of crushed coarse particles was evaluated with gravel aggregates in Blends I, N-Q. The effect of the amount of natural sand in the aggregate blend was evaluated in Blends I-M. This evaluation combines the effects of particle shape and texture and fine aggregate gradation.

In order to fully evaluate the influence of aggregate gradation and particle shape and texture on permanent deformation of HMA mixtures, the research study included both a laboratory evaluation of aggregate and HMA mixture characterization tests and a field evaluation of HMA pavements after traffic. The overall research plan involved six phases and is outlined below and illustrated by flow chart in Figure 2.

Laboratory Evaluation

1. Phase I - Aggregate characterization of composite blend, coarse and fine aggregate fractions of each of the eighteen selected aggregate blends. After the labstock materials were tested and fabricated to meet the desired test aggregate gradations, each blend was evaluated to characterize the particle shape and surface texture. Each blend was separated on the No. 4 sieve so that the coarse and fine aggregate fractions could be evaluated. The laboratory test plan for aggregate characterization of the eighteen aggregate blends is shown in Figure 3.

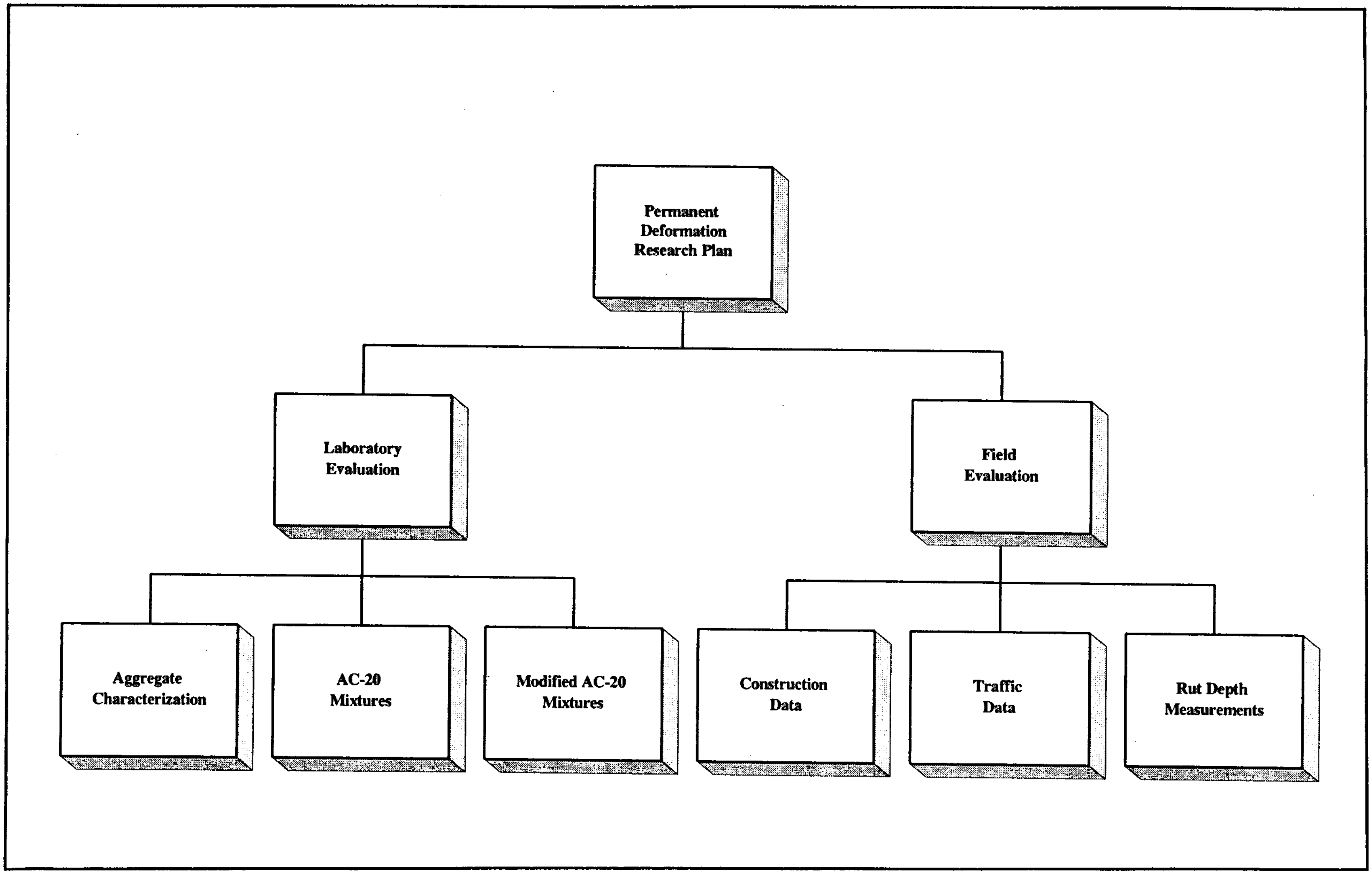


Figure 2. Overall Research Test Plan

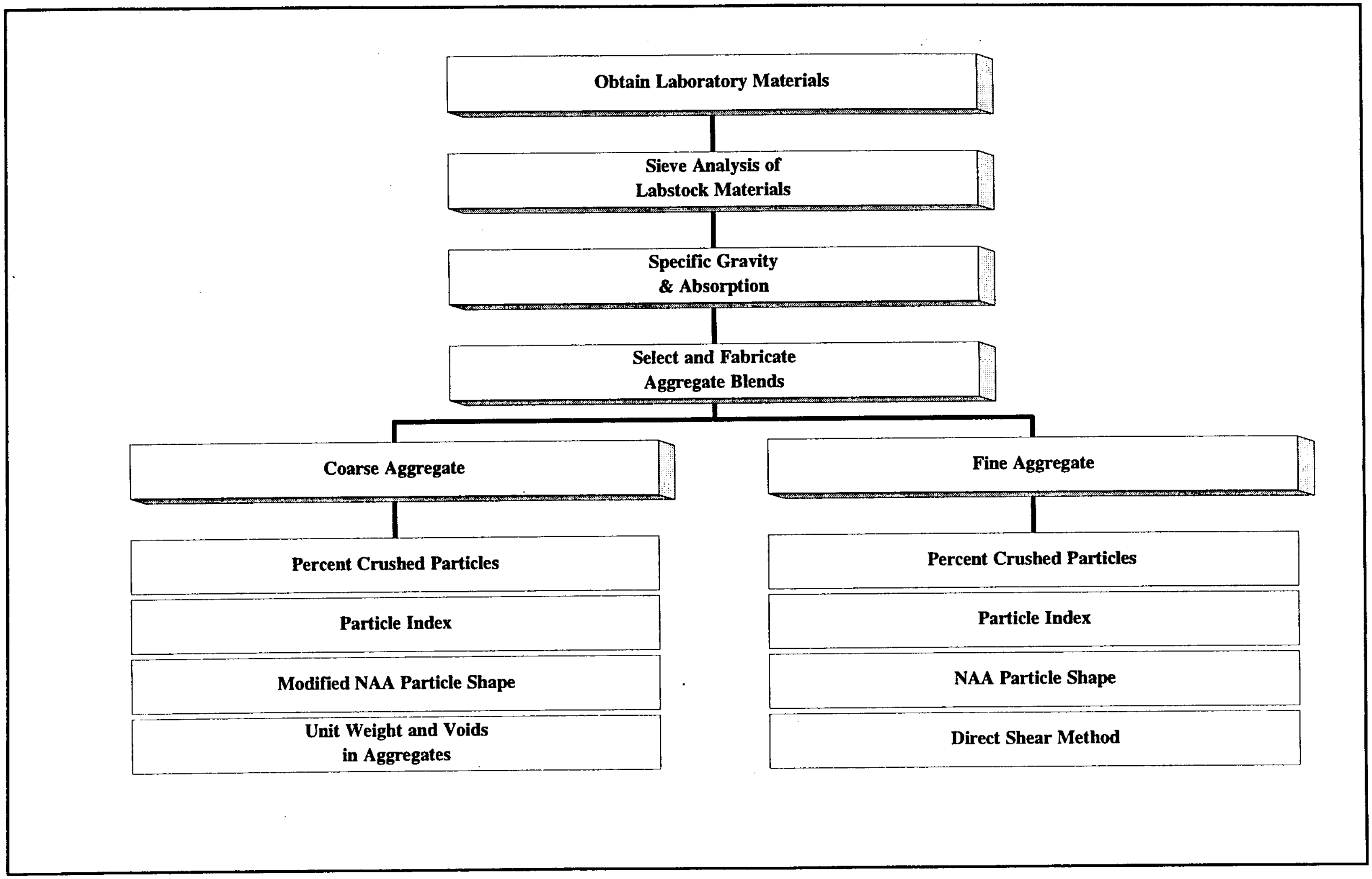


Figure 3. Laboratory Test Plan for Aggregate Characterization

2. Phase II - Preparation and evaluation of eighteen HMA mixtures produced with AC-20 binder. A volumetric mix design was conducted on each test gradation aggregate blend and an optimum asphalt content was selected at 4 percent air voids using a gyratory compactive effort equivalent to a 75 blow compactive effort. The details of the gyratory compaction are discussed in Chapter IV. The laboratory test plan conducted to evaluate engineering properties of each HMA mixture at the optimum asphalt content is shown in Figure 4. Details and descriptions of each test procedure are presented and discussed in Chapter IV. This laboratory testing determined the range of HMA mix properties that would be expected using material meeting the P-401 specification and the impact of deviations (shape of gradation curve and blends with different particle shapes and textures) on engineering properties of HMA mixtures.

3. Phase III - Preparation and evaluation of eight selected aggregate blends produced with two polymer modified AC-20 binders (sixteen HMA mixtures). The asphalt modifiers used in this laboratory study were a SBS (Styrene-butadiene-styrene) and a LDPE (Low density polyethylene). A volumetric mix design was conducted for each mixture in order to select an optimum asphalt content at 4 percent air voids. The same engineering property tests that were conducted on the AC-20 HMA mixtures were also conducted on these specimen. This phase of laboratory testing would determine the effectiveness of asphalt modification to improve the strength or rutting characteristics of HMA mixtures with substandard aggregates. Figure 5 illustrates the various HMA mixtures that were evaluated to determine the effects of aggregate gradation and particle shape and texture on permanent deformation characteristics of HMA mixtures.

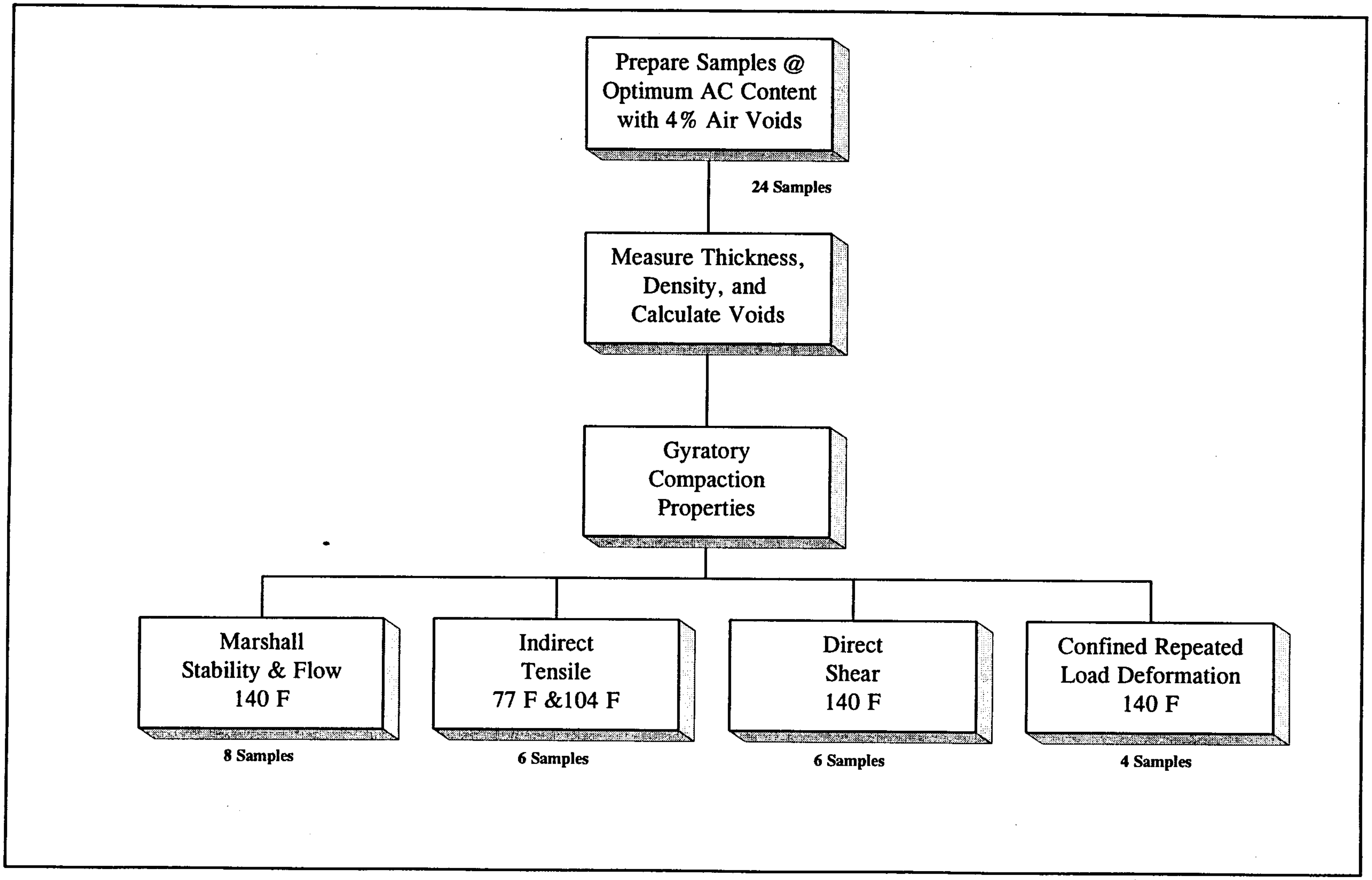
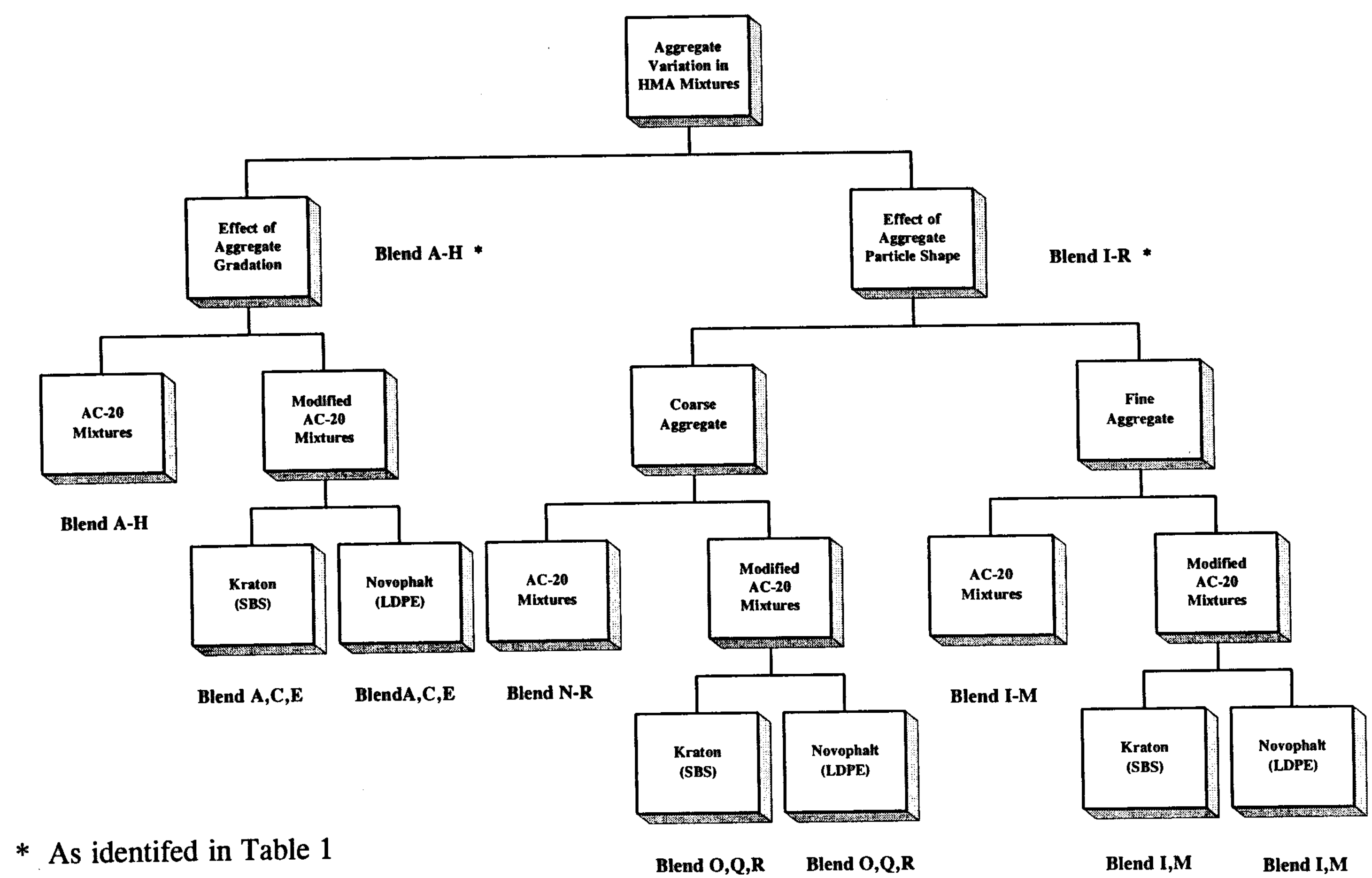


Figure 4. Laboratory Tests for Each HMA Mixture



* As identifed in Table 1

Figure 5. Flow Chart of Variations in HMA Mixtures

Field Evaluation

4. Phase IV - Selection and construction of ten field test items. Based on the findings of the laboratory study, several aggregate blends and two asphalt binders were selected to evaluate different aggregate gradations and particle shapes and textures under actual traffic loading conditions. The SBS modified AC-20 binder was used with five aggregate blends to evaluate the benefits of asphalt modification. A sample of plant-mixed HMA was obtained and evaluated for each test item in order to characterize the as constructed HMA properties.

5. Phase V - Description of load cart assembly and distribution of traffic. The trafficking of the field test items was conducted with a load cart assembly that simulated heavy aircraft loads and tire pressures. The load cart assembly was comprised of a single wheel (1 ft wide) loaded with 40,000 pounds at a tire inflation pressure of 200 psi. A normal distribution of traffic was applied over a 60 in. traffic lane. A total of 12,000 passes was applied to each item.

6. Phase VI - Measurement of rut depths and evaluation of field performance. Rut depth measurements were taken at various intervals and at completion of trafficking. Rut depths were measured transversely across each test item with a straightedge laid flat on the HMA pavement surface. Three field cores were taken from each item and tested with the confined repeated load deformation (triaxial cyclic creep) test to validate this test procedure's potential to predict rutting.

CHAPTER IV MATERIALS, TEST EQUIPMENT, AND PROCEDURES

MATERIALS

The primary objectives of this study were to quantify the aggregate particle characteristics, to evaluate the relationship between these aggregate properties and the rutting potential of HMA mixtures, and to determine the benefits of asphalt modification with substandard aggregates on the permanent deformation characteristics of HMA mixtures. In order to achieve these goals, the laboratory testing program included the following variables:

1. Aggregate gradation.
2. Type of aggregate.
3. Type of asphalt binder.
4. Percentage of crushed particles.
5. Percentage of natural sand.
6. Type of aggregate characterization test.
7. Type of asphalt concrete mixture test.

Aggregates

Three coarse aggregates (crushed limestone, crushed gravel, and uncrushed gravel) and five fine aggregates (crushed limestone, crushed gravel, uncrushed gravel, coarse natural sand, and fine natural sand) were incorporated in the HMA mixtures. Each of these aggregate materials, except the natural sand materials, were processed by screening into individual sieve sizes to accurately fabricate the desired test gradations. The physical properties including gradation, specific gravities, and absorption for each aggregate type and size are summarized in Appendix A. Each aggregate type was considered nonabsorptive due to their low average absorption values (limestone - 0.2 percent, crushed and uncrushed gravel - 1.4 percent, and coarse and fine natural sands - 0.5 percent).

Asphalt Binders

This laboratory study incorporated the use of three asphalt binder materials. Since the primary goal or objective of Phase II of this laboratory study was to investigate the influence of aggregate gradation and particle shape on the strength and permanent deformation characteristics of HMA mixtures, an AC-20 asphalt cement was selected because it is considered a medium hard asphalt cement, most commonly used asphalt cement, and would not interfere with evaluating the aggregate properties. The physical properties for the AC-20 asphalt cement are presented in Table 2. The primary purpose of Phase III of this laboratory study was to determine the effectiveness of modified binders to improve the strength and rutting characteristics of HMA mixtures with various substandard aggregate gradations and particle shapes. For this phase of the laboratory study, an AC-20 modified with 5 percent SBS, and an AC-20 modified with 6 percent LDPE were mixed with eight selected aggregate blends. The physical properties of these materials are also presented in Table 2.

Table 2. Physical Properties of Asphalt Binder Materials

Test	AC-20	AC-20 + SBS	AC-20 + LDPE
Viscosity - absolute, 140°F, P	2246	25,963	11,016
Viscosity - kinematic, 275°F, Cst	492	1878	731
Penetration - 77°F, 100 g, 5 sec, 0.1 mm	75	48	56
Flash point - Cleveland Open Cup, °F	550	534	547
Solubility in trichloroethylene - percent	99.93	99.95	--
Test on residue from thin film oven test			
Percent weight loss	0.48	0.11	0.13
Viscosity - 140°F, P	6602	21,820	13,251
Ductility - 77°F, 5 cm/min, cm	71	143	39

TESTS FOR AGGREGATE CHARACTERIZATION

Aggregate particles have been characterized with various tests and methods. The characterization of aggregate shape (angularity) and surface texture (roughness) is essential in selecting aggregates to produce high quality asphalt mixtures for heavy duty pavements. Based on the findings from the literature review, the test methods and procedures used to evaluate and characterize the coarse and fine aggregates of each aggregate blend are listed in Table 3. The laboratory equipment and test procedures used in this laboratory study are described and discussed in the following paragraphs.

Table 3. Aggregate Characterization Tests

Coarse aggregate	Fine aggregate
Percent crushed particles	Percent crushed particles
Particle Index	Particle Index
Unit weight and voids	Direct shear
Modified NAA particle shape and texture	NAA particle shape and texture

Percent Crushed Particles

This test method (CRD-C 171) is a procedure for determining the percentage of crushed or fractured particles in an aggregate sample by visual inspection. (57) This method is currently being proposed as an American Society for Testing and Materials (ASTM) standardized test method. This method involves subjectively separating crushed or fractured aggregate particles from uncrushed aggregate particles. The percentage of crushed particles is expressed by weight or count. A "crushed" particle is defined as an aggregate particle that has at least two mechanically induced fractured faces.

The labstock materials used in this laboratory study were crushed limestone, crushed gravel, uncrushed gravel and natural sand. The percent crushed particles for the crushed gravel stockpile were determined by visual inspection (97 percent crushed coarse and 100 percent crushed fine). Since each aggregate blend was fabricated with individual sieve sizes of these labstock materials, the percent crushed particles for the aggregate blends were determined from batch weights and the percent crushed count for that aggregate.

Particle Index

The Particle Index Test was originally developed by Huang for the evaluation of coarse aggregates for a soil-aggregate material. (34) This test was based on the concept that the aggregate void characteristics would indicate the characteristics of the aggregate's shape, angularity, and surface texture for a one-sized aggregate. The original test procedure and equipment have been modified and standardized by ASTM in Test Method D 3398. (58)

The equipment required is simple consisting of cylindrical steel molds ranging in diameters from 2 to 8 in., depending on the aggregate size. This test method requires that the aggregate sample be separated into individual sieve fractions and washed and oven-dried. Each size fraction is separately compacted in three equal lifts in the cylindrical mold using a tamping rod. This compaction is applied with two efforts, 10 and 50 drops per layer. Each tamp is dropped from a height of 2 in. above the surface of the layer being compacted. The percent voids in the aggregates for each compactive effort is calculated using the weight of the aggregate in the cylindrical mold and the bulk gravity of the aggregate. Based on the percentages of voids at 10 and 50 drops, the Particle Index value of an aggregate is calculated using the following equation:

$$Ia = 1.25\ V_{10} - 0.25\ V_{50} - 32.0 \tag{1}$$

where

Ia	=	Particle Index value
V_{10}	=	percent voids with 10 drops per layer
V_{50}	=	percent voids with 50 drops per layer

The weighted Particle Index value for an aggregate blend having multiple aggregate sizes is computed on the basis of the weight percentage of each size fraction in the aggregate gradation. When a sieve size is represented by less than 10 percent of the grading, the average Particle Index value for the next coarser and finer size is used.

NAA Particle Shape and Texture

This test method has recently been adopted by ASTM (Test Method C 1282) but was developed by the National Aggregate Association (NAA) as a simple practical routine test to measure aggregate particle shape and surface texture of fine aggregate (minus No. 4 sieve material). (59) This test method determines the loose uncompacted void content of fine aggregate by allowing the fine aggregate particles to fall loosely from a specified height through the orifice of a funnel into a calibrated cylinder. The excess material is struck off and the aggregate in the cylinder is weighed. The uncompacted void content of the fine aggregate sample is calculated using the weight of aggregate and the bulk specific gravity of the aggregate. The test equipment dimensions are summarized in Table 4 and the test apparatus is shown in Figure 6.

Table 4. NAA and Modified NAA Test Apparatus Dimensions

Parameters	NAA test apparatus	Modified NAA test apparatus
Aggregate size	No. 4 to No. 100	3/4 in. to No. 4
Bin diameter, in.	4.0	6.0
Orifice diameter, in.	0.5	4.0
Drop distance, in.	4.5	4.5
Volume of cylinder, $in.^3$	6.1	171

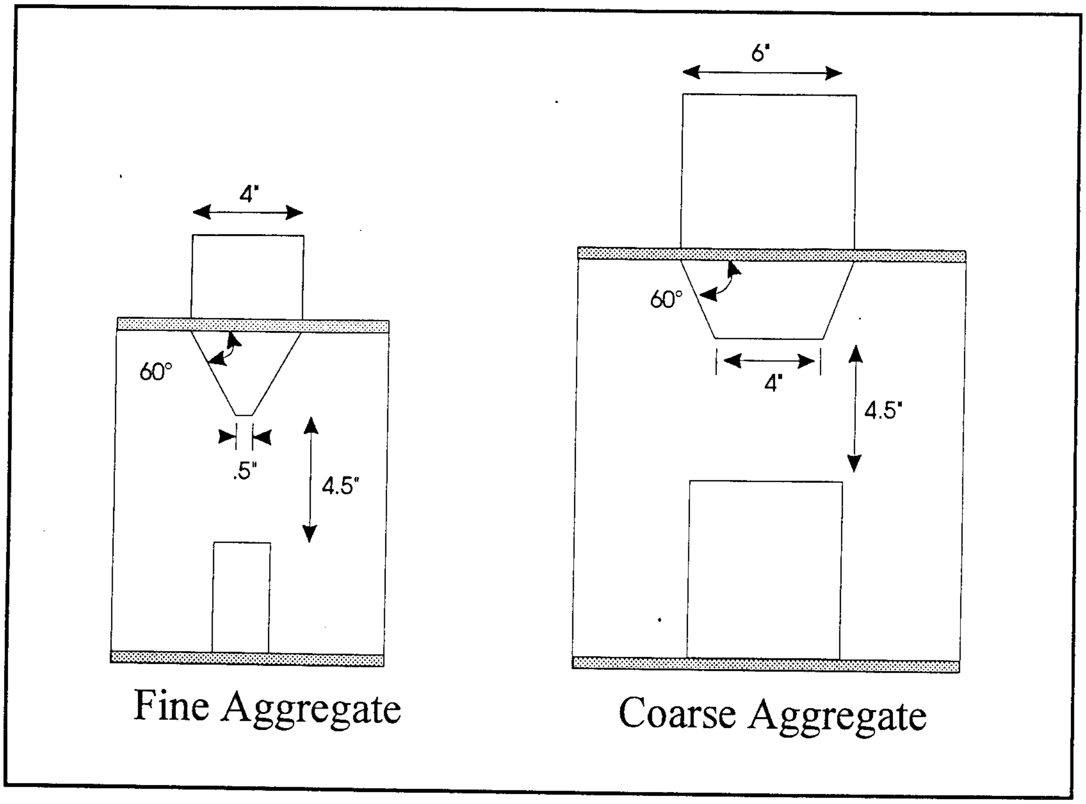


Figure 6. NAA and Modified NAA Particle Shape and Texture Test Apparatus

Three procedures are included in the NAA test method for measurement of void content using graded fine aggregate (standard grading or as-received grading) or through the use of several individual size fractions. Method A uses a standard fine aggregate grading of 190 grams that can be obtained from individual sieve fractions. The standard grading consists of the sizes and weights listed in Table 5.

Table 5. Aggregate Fractions and Weights for NAA Method A

Sieve size fraction	Mass, g
No. 8 to No. 16	44
No. 16 to No. 30	57
No. 30 to No. 50	72
No. 50 to No. 100	17
Total	190

Method B uses 190 grams of three individual aggregate size fractions: No. 8 to No. 16, No. 16 to No. 30, and No. 30 to No. 50. Each size fraction is tested separately and the uncompacted void content for the fine aggregate is computed as the average of the three size fractions.

Method C uses 190 grams of as-received material that passes the No. 4 sieve. The uncompacted void content of a fine aggregate for this test method is calculated using the following equation:

$$UCV = \frac{Vol - \left(\frac{Mass}{Bulk}\right)}{Vol} \times 100 \qquad (2)$$

where

UCV = uncompacted voids in fine aggregate, percent

Mass = mass of aggregate in cylinder, grams

Bulk = bulk specific gravity of fine aggregate

Vol = volume of cylinder, cubic centimeters

Modified NAA Particle Shape And Texture

The NAA particle shape and texture apparatus was modified in order to test and evaluate larger coarser aggregate particles (No. 4 to 3/4 in.) with the same concept of uncompacted voids. The basic differences in the test apparatus was the size of the funnel orifice and the volume of the cylinder. These dimensions were enlarged to account for the larger coarser aggregate particles and to have the approximate same aggregate size to orifice opening ratio. The modified test apparatus dimensions are very similar to the dimensions specified for the "Pouring Test" developed by Ishai and Gelber. (29) The height of aggregate fall was kept constant to insure the energy levels were consistent for both test methods. The dimensions of the modified test apparatus are summarized in Table 4 and the test apparatus is shown in Figure 6.

The measurement of the uncompacted void content for coarse aggregate particles is conducted using two gradings. Method 1 uses 5,000 grams of as-received material that passes the 3/4 in. sieve but is retained on the No. 4 sieve. The uncompacted void content is calculated using Equation 2. Method 2 uses 5,000 grams of three individual aggregate size fractions: 3/4 in. to 1/2 in., 1/2 in. to 3/8 in., and 3/8 in. to No. 4. Each size fraction is tested separately and the uncompacted void content for each size fraction is determined. The uncompacted void content for the coarse aggregate particles is calculated as an average of the three individual size fractions or by weighted average using the weight percentage of each size fraction in the coarse aggregate gradation.

Direct Shear Method

This test method is used to determine the shear strength and angle of internal friction of fine aggregate materials under different normal stress conditions. The shear strength of a fine aggregate is controlled by the angle of internal friction and the normal effective stress. The shear failure of a fine aggregate is determined by two major factors, rolling and slipping. The sliding resistance of aggregate particles for a given normal stress is determined by the angle of internal friction, particle shape, angularity, and texture. Theoretically, this concept should produce a valid relationship between the angle of internal friction and the characteristics of aggregate shape, angularity, and surface texture.

The direct shear test (EM 1110-2-1906, Appendix IX) (60) is performed on an oven-dried sample of approximately 140 grams of fine aggregate. The fine aggregate sample is placed in a square box in which the top half can slide over the bottom half (Figure 7). The box dimensions are 3.0 by 3.0 in. and 0.5 in. thick. The fine aggregate is poured at a constant rate into the shear box for each aggregate blend. A normal force or stress is applied to the top of the box while a horizontal shearing force is applied so that the failure will occur along a horizontal plane at the midheight of the sample. This shear test was conducted at three normal stress levels (1TSF, 2TSF, and 3TSF) of each aggregate blend. The angle of internal friction was determined by plotting shear stress versus normal stress and constructing a "best fit" line through the data points. The angle of internal friction is the angle between the constructed "best fit" line and the horizontal (x) axis.

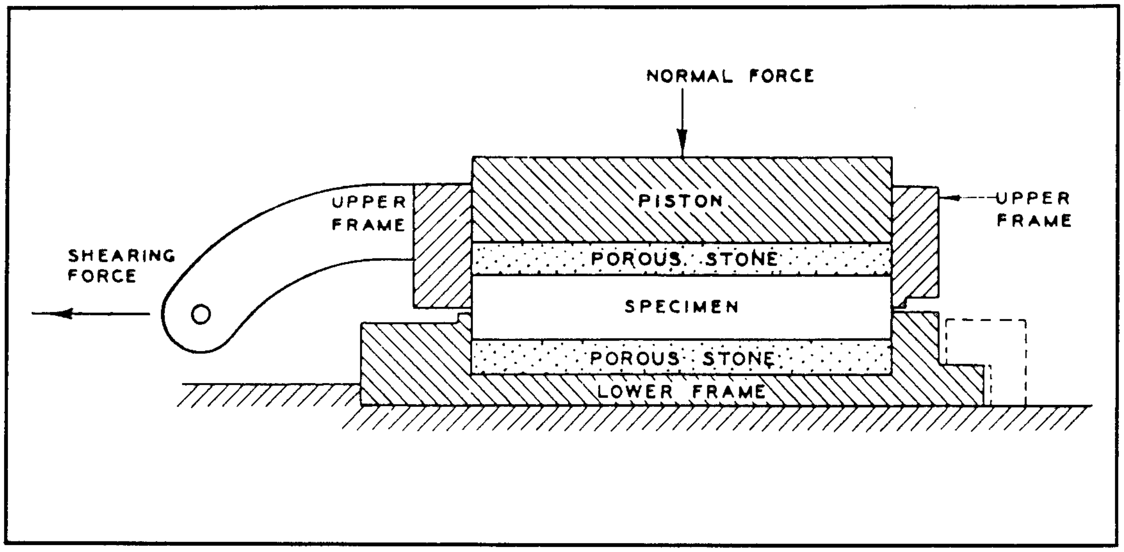


Figure 7. Schematic Diagram of Direct Shear Box (60)

Unit Weight and Voids in Aggregate

This test method (ASTM C 29) determines the unit weight of fine, coarse, or mixed aggregate blends in a compacted or loose condition and calculates the voids in the aggregate matrix based on the unit weight. The voids calculated with this method are the space between the aggregate particles not occupied by solid mineral matter. These voids do not include any voids within the aggregate particles, either permeable or impermeable. (61)

The test method is basically simple and straight-forward and requires approximately 5,000 grams of oven-dried aggregate to be placed in a specified cylinder (0.1 ft^3 for aggregates smaller than 1/2 in.) in a compacted or loose condition. ASTM C 29 test method allows three procedures for determining the unit weight of an aggregate, rodding, jigging, and shoveling procedures. The rodding and jigging procedures produce compacted samples while the shoveling procedure produces a loose sample. The rodding procedure specifies that the aggregate material be compacted in three equal lifts with 25 strokes of a rod evenly distributed over the surface. The shoveling procedure requires that the aggregate be discharged from a shovel or scoop not more than 2 in. above the cylinder. After each procedure is completed, the excess aggregate particles are leveled off with a straight-edge and the weight of aggregate is determined. The void content of the aggregate matrix is calculated using Equation 2.

TESTS FOR HMA MIXTURE EVALUATION

In order to complete the objectives of this laboratory study, several test procedures were used to determine the effects of aggregate gradation and particle shape and texture on the engineering properties (strength and rutting characteristics) of HMA mixtures. Marshall stability and flow, indirect tensile strength, direct shear strength, and confined repeated load deformation (triaxial cyclic creep) were measured. The Corps of Engineers Gyratory Testing Machine (GTM) was used to measure HMA mixture properties during compaction of specimens.

Volumetric and Marshall Properties

A volumetric mix design was conducted on all eighteen aggregate blends to determine the optimum asphalt contents. The compactive effort was modified and the gyratory compaction process was used instead of the Marshall impact hammer. The optimum asphalt content was selected at 4 percent air voids (voids total mix) to reduce the effect of the asphalt content on the mix properties and enhance the influence of aggregate gradation and particle shape and texture. The measured HMA properties included void parameters, Marshall stability, and flow for each HMA mixture at its optimum asphalt content.

The Marshall stability and flow test was conducted according to ASTM D 1559 using a Marshall testing machine which is equipped with an automatic plotting device for graphing stability curves. (58) The Marshall stability of an asphalt mixture is an indicator of the mix strength defined as the resistance to deformation or plastic flow under a load. (62) Stability has also been defined as a measurement of the mass viscosity of an asphalt-aggregate mixture and is affected by aggregate shape and texture and the viscosity or stiffness of the asphalt cement. (4) The flow value is an indicator of mix plasticity measured as the deformation at failure or maximum load of the stability test.

Gyratory Testing Machine

Compaction of asphalt concrete mixtures using the gyratory method applies normal forces to both the top and bottom faces of the material confined in cylindrically-shaped molds. Normal forces at designated pressures are supplemented with a kneading action or gyratory motion to compact the HMA material into a denser configuration with aggregate particle orientation more consistent with in-place pavements. The U.S. Army Corps of Engineers developed a method, procedure, and equipment using this compaction procedure. (63,64,65)

The gyratory compaction method (ASTM D 3387) involves placing HMA material into a 4-in.-diameter mold and loading into the GTM at a prescribed normal stress level which represents anticipated traffic contact pressure. (58) The asphalt concrete material and mold are then rotated through a 1-degree gyration angle for a specified number of revolutions of the roller assembly. This compaction process produces stress-strain properties that are representative of those in field compacted specimen. A schematic of the gyratory compaction process is shown in Figure 8.

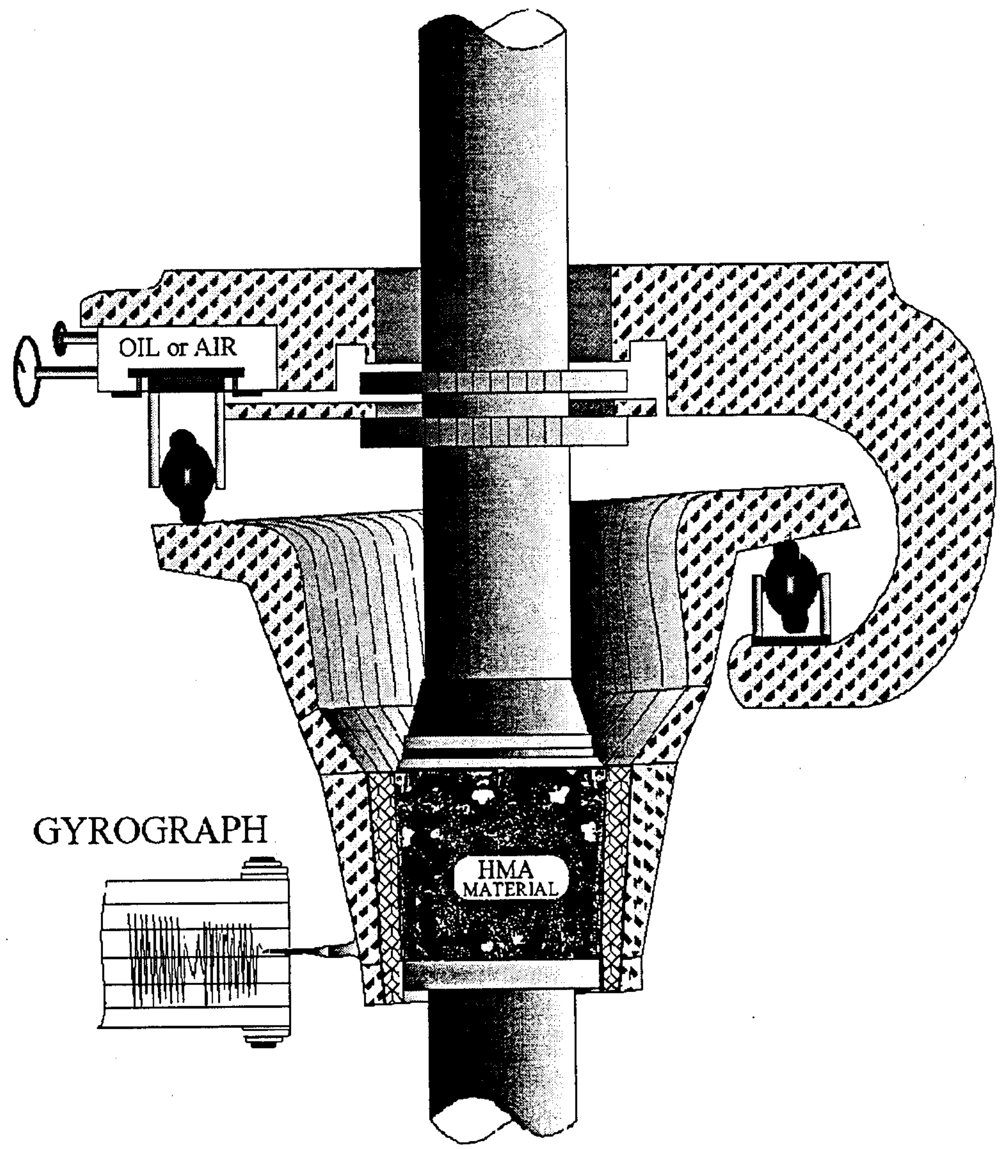


Figure 8. Schematic of Gyratory Compaction Process

Model 4C and Model 8A/6B/4C GTM's (Figure 9) were used to compact all laboratory specimen in this aggregate laboratory study. Previous research with the GTM has suggested that the laboratory tests will simulate field behavior and performance under traffic when asphalt concrete mixtures are compacted at stress levels similar to anticipated field traffic conditions. (66,67) The gyratory compactive effort used in this laboratory study was a 200 psi normal stress level, 1-degree gyration angle and 30 revolutions of the roller assembly which is equivalent to the standard 75-blow Marshall hand hammer effort (11,39,62). This compaction effort produced asphalt concrete specimen that satisfy the Marshall specimen dimensions of 4 in. in diameter and 2 1/2 in. thick.

The gyratory compaction method using the GTM produces a gyratory graph or gyrograph that can be used to evaluate the asphalt concrete mixture behavior during compaction (Figure 10). The gyrograph indicates the relative stability or plastic behavior of the mixture during the compaction process. The gyrograph indicates an unstable mixture when the gyrograph spreads or widens. A gyrograph that does not spread is considered stable under that loading condition. The gyrograph also produces two indices that describe the relative stability of an asphalt concrete mixture. The ratio of the maximum width to the minimum width of the gyrograph is called the Gyratory Stability Index (GSI) (Equation 3). A GSI value greater than 1.0 indicates an unstable plastic mixture. The ratio of the minimum width to the initial width (machine setting) is called the Gyratory Elasto-Plastic Index (GEPI) (Equation 4). The GEPI value is an indicator of the quality of the aggregate. The GEPI is a measure of the shear strain experienced by the mixture and is an index of the angle of internal friction of the aggregate. (62,64)

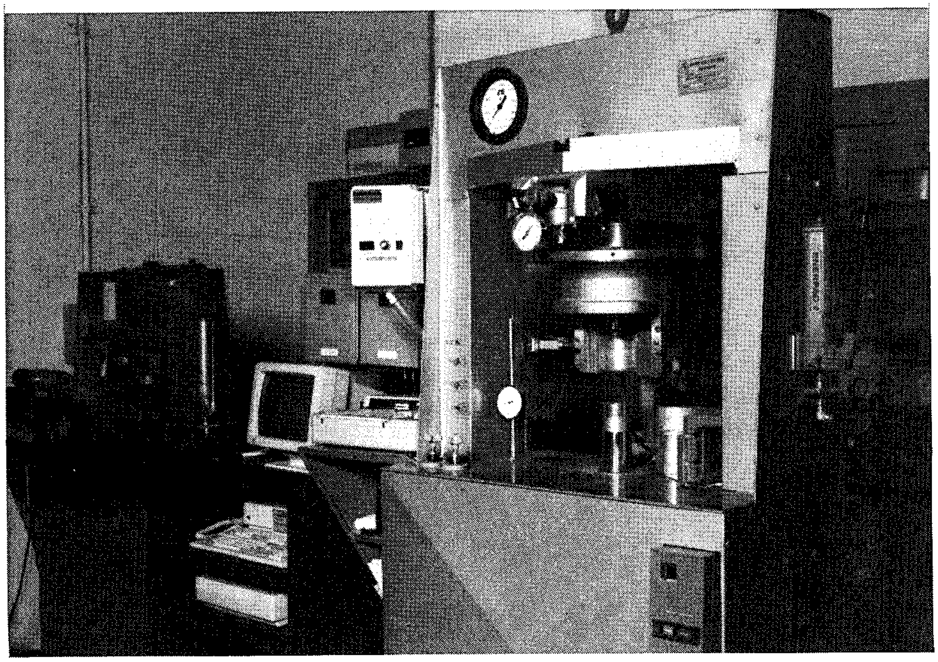


Figure 9. WES Model 4C and 8A/6B/4C Gyratory Testing Machines

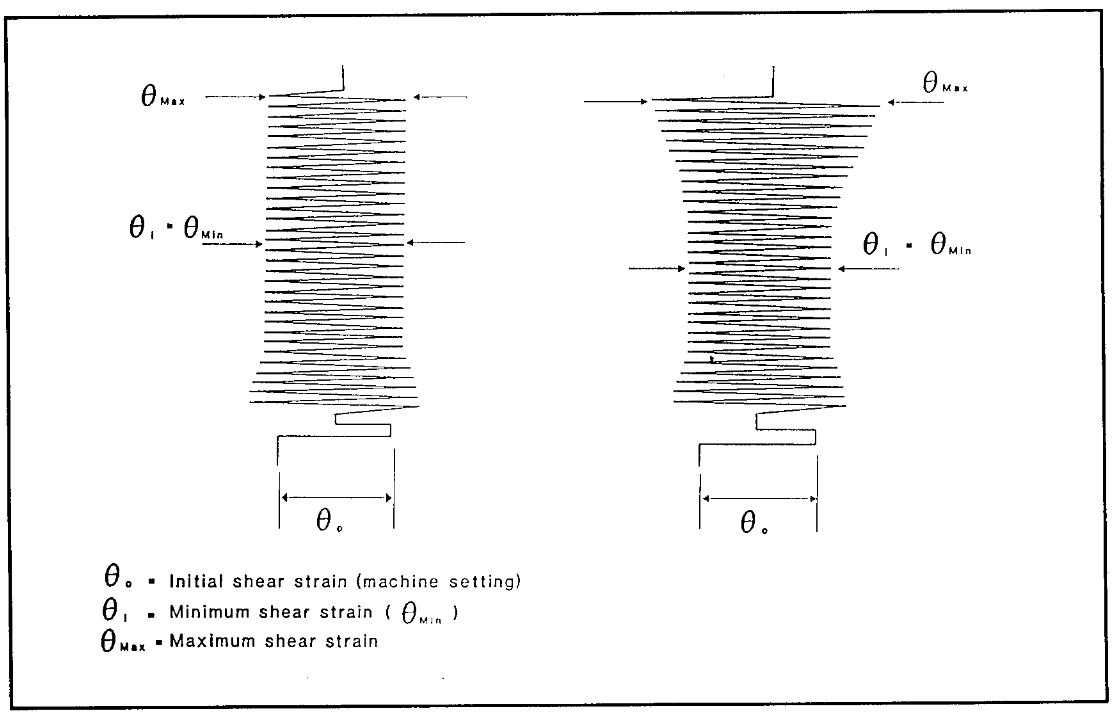


Figure 10. Typical Gyrograph (63)

$$Gyratory\ Stability\ Index\ (GSI) = \frac{\Theta_{max}}{\Theta_{min}} \tag{3}$$

$$Gyratory\ Elasto\text{-}Plastic\ Index\ (GEPI) = \frac{\Theta_{min}}{\Theta_0} \tag{4}$$

The gyratory shear strength value is a third measure that evaluates the quality of the HMA mixtures. The gyratory shear strength value is the shear strength of compacted specimen determined from the static roller pressure readings. This gyratory shear strength property has been reported to be an effective measurement to evaluate HMA mixtures and to delineate good mixtures from poor mixtures. (68,69)

Indirect Tensile

The indirect tensile test was developed to indirectly determine the tensile strengths of materials by placing a cylinder of material horizontally between two loading plates and loading the specimen across its diameter until failure (Figure 11). This loading configuration subjects the centerplane between the loading plates to a nearly uniform tensile stress which results in a failure of the material. This test procedure has been used to test soils, concrete, and asphalt materials, and has been used by engineers to compute fundamental properties of materials. (70)

ASTM Method D 4123 provides guidance on indirect tensile testing of asphalt concrete mixtures. (58) This test procedure was conducted on specimen produced at optimum asphalt content at two test temperatures, 77°F and 104°F. The specimen were cured in an oven at the appropriate temperature for 2 hours before testing. The vertical

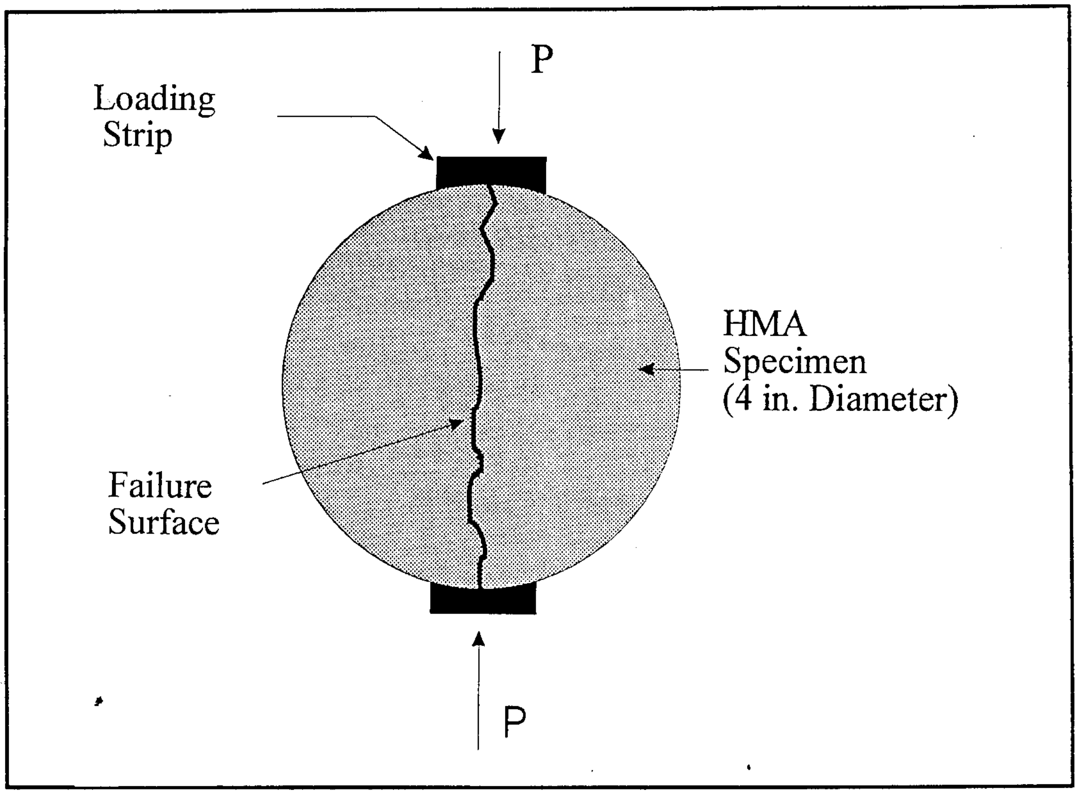


Figure 11. Schematic of Indirect Tensile Test

load is applied to produce a constant deformation rate of 2 in. per minute until failure. The ultimate load is recorded at failure and is used to calculate the tensile strength. The tensile strength is calculated according to ASTM D 4123 with the following equation:

$$TS = 2P/\pi\ t\ D \qquad (5)$$

where

TS = tensile strength, psi

P = ultimate load required to fail specimen, lbs.

t = thickness of specimen, in.

D = diameter of specimen, in.

This testing procedure was conducted on a minimum of three specimen for each of the thirty-four HMA mixtures at both temperatures.

Direct Shear

The direct shear test is used to determine the shear strength of HMA mixture under different normal stress conditions. The shear strength of a HMA mixture is controlled by the cohesion of the asphalt binder, the angle of internal friction, and the effective normal stress. For a given normal stress and asphalt binder type, the shear strength of a HMA mixture is controlled by the aggregate properties (i.e. gradation, angularity, shape, and surface texture) and compaction.

The direct shear test for HMA mixtures was conducted in a device illustrated in Figure 12. A standard Marshall specimen (4-in.-diameter and 2.5-in.-thick) was placed in the shearing apparatus and tested at 140°F. The simple shear assembly was placed in the Instron machine which applied and measured the shear load and displacement during the test. The load was applied across the shear plane at a rate of 1/2 in. per minute. The direct shear test was conducted at three normal stress levels, 100 psi, 200 psi, and 300 psi. Two test replicates were conducted for each test condition. The angle of internal friction and cohesion (shear strength at normal stress equal to zero) were determined by plotting shear stress versus normal stress and constructing a "best fit" line through the data points. The angle of internal friction is the angle between the constructed "best fit" line and the horizontal (x) axis and the cohesion value is the intercept of the vertical (y) axis.

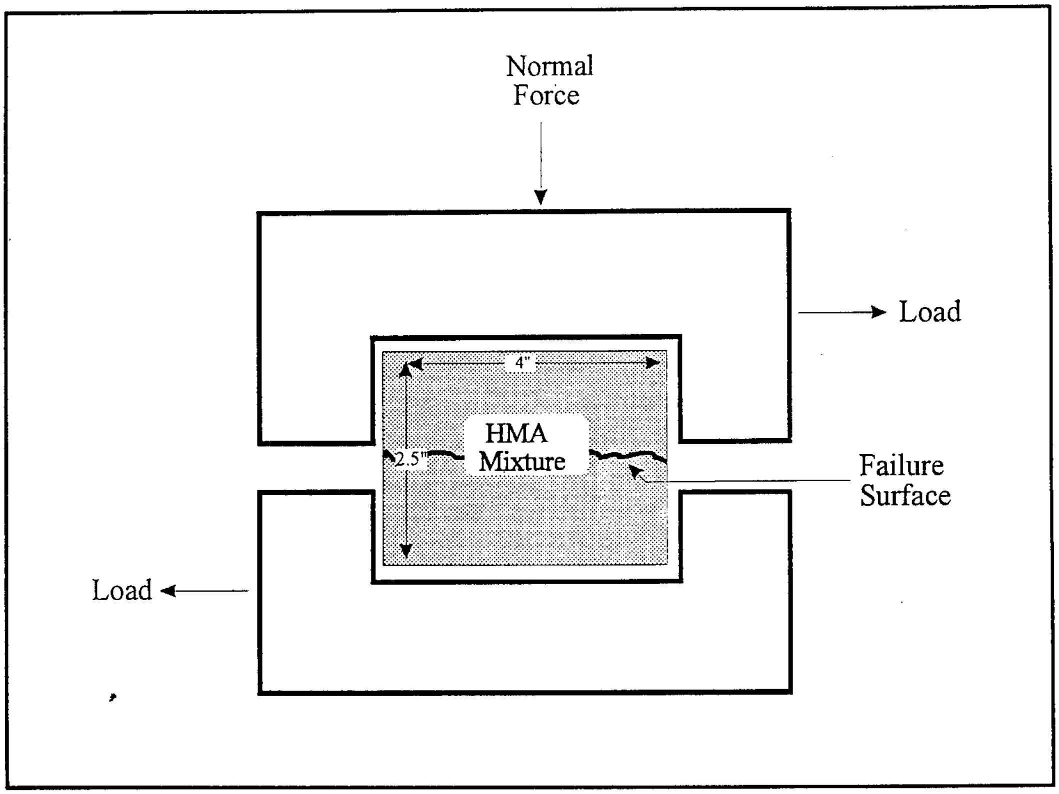


Figure 12. Schematic of Direct Shear Test

Confined Repeated Load Deformation

The confined repeated load deformation (triaxial cyclic creep) test was used to evaluate the rutting potential of HMA mixtures and to determine the effectiveness of asphalt modification to improve the rutting characteristics of these mixes. This test equipment and evaluation was developed by WES specifically for this research on the basis of recent work conducted at the National Center for Asphalt Technology (NCAT) at Auburn University that showed the confined repeated load deformation test provided the best laboratory indication of rutting. (44,71,72) Button and Perdomo (25) and Anderton et al. (73) stated that triaxial cyclic or confined repeated load deformation tests at high temperatures were the best approaches to evaluate permanent deformation since this type test more closely reproduced the in situ pavement conditions under traffic.

The confined repeated load deformation tests were performed on individual Marshall specimen that were 2.5 in. thick and 4 in. in diameter. The specimen was placed in the triaxial chamber with smooth, dense-graded paper on each end and a rubber membrane around the sides. The triaxial chamber was then placed in an environmental chamber at 140°F for a minimum of 2.5 hours. The triaxial chamber was pressurized with a confining pressure of 40 psi for 5 minutes. Each specimen was preconditioned with a 1.5 psi preload and then a 10 psi cyclic stress was applied for 30 cycles. The cyclic or repeated load was applied with a 0.1 second load application and a 0.9 second rest period.

The loading portion of the test applied a repeated cyclic load (200 psi) for 60 minutes and then the loading was released for 15 minutes for the rebound phase. The applied deviator stress was 200 psi. The test conditions are illustrated in Figure 13. The deformations and loads were recorded at various times during the creep and rebound phases. These measurements were used to calculate creep modulus (stiffness) and permanent strain values. The confined repeated load deformation test was conducted at 140°F which was considered maximum pavement temperature.

The results of the confined repeated load deformation test can be used in several ways to evaluate asphalt concrete mixtures. The amount of strain after the creep and rebound phases of the test indicates the asphalt mixture's potential for permanent deformation. Smaller axial strains and lower creep strain values indicate a stable asphalt mixture. The creep modulus value indicates the asphalt mixture's stiffness. High creep modulus values should indicate minimum potential permanent deformation. The creep modulus value is calculated using the following equation:

$$CM = \frac{S}{\frac{D}{H}} \qquad (6)$$

where

CM = creep modulus value, psi

S = deviator stress - 200 psi

H = height of specimen, in.

D = axial deformation, in.

Another test result that can be used to evaluate the rutting potential of an asphalt concrete mixture is the slope of the log cumulative strain versus log time curve shown in Figure 14. The higher the slope value, the greater the potential for rutting in an asphalt concrete mixture. (68,74)

The slope of the creep curve is defined as:

$$M = \frac{\log E_{T2} - \log E_{T1}}{\log T_2 - \log T_1} \qquad (7)$$

where

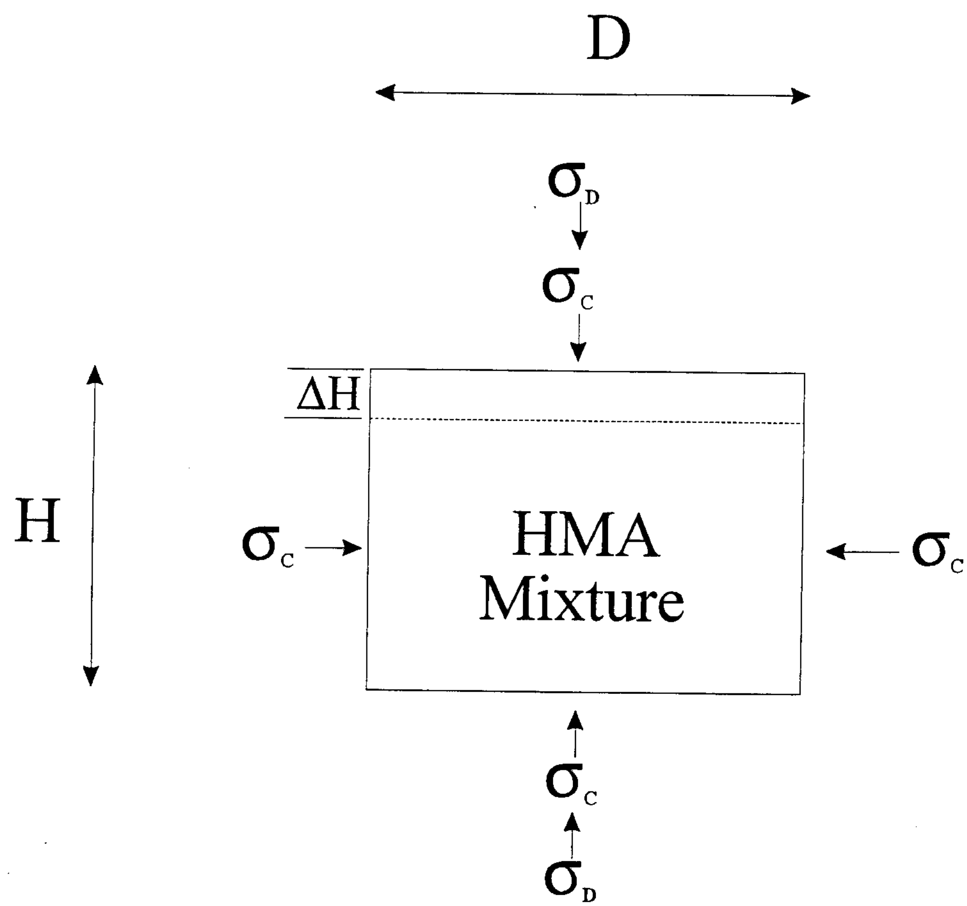
M = slope of log - log creep curve

E_{T2} = cumulative strain at 3,600 seconds

E_{T1} = cumulative strain at 900 seconds

T_1 = 900 seconds

T_2 = 3,600 seconds



Where:

H = height of specimen (in)

D = diameter of specimen (in)

ΔH = permanent deformation (in)

σ_C = confining pressure (40 psi)

σ_D = cyclic deviator stress (200 psi)

Figure 13. Schematic of Confined Repeated Load Deformation Test

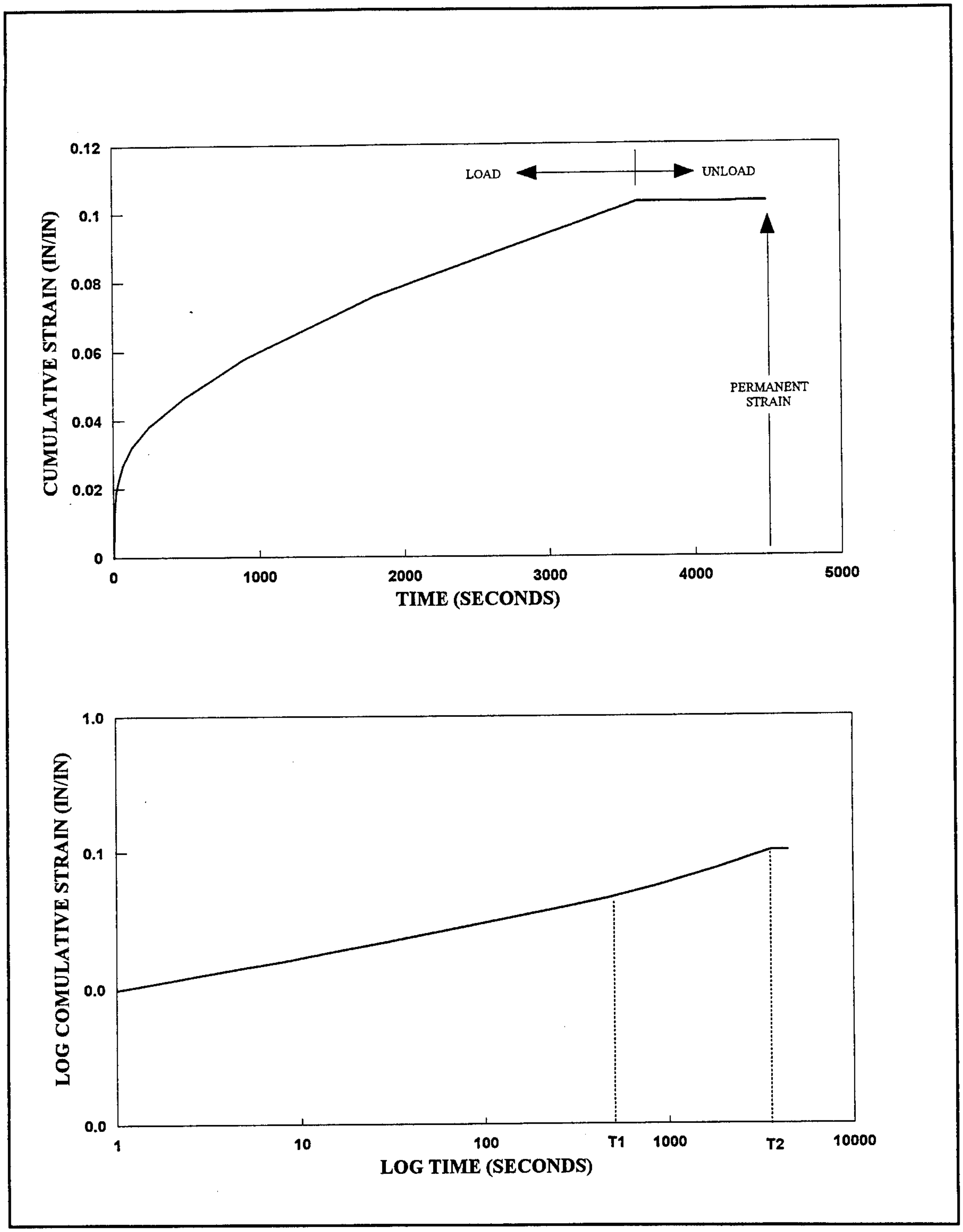


Figure 14. Typical Confined Repeated Load Deformation Curves

CHAPTER V LABORATORY EVALUATION

The laboratory evaluation outlined in the Plan of Study was conducted to determine the impact of aggregate properties on HMA mixture strength and rutting characteristics. The focus of the study was to investigate the effects of aggregate gradation and particle shape and texture on permanent deformation of HMA mixtures. The laboratory study also evaluated the benefits of asphalt modification to improve permanent deformation characteristics of HMA mixtures with substandard aggregates. The laboratory study was conducted in three phases: 1) aggregate characterization, 2) evaluation of HMA mixtures, and 3) evaluation of modified HMA mixtures.

AGGREGATE CHARACTERIZATION

Presentation of Test Results

This section presents and discusses the results of the aggregate characterization tests conducted on selected test aggregate gradations. The laboratory testing program for this aggregate study was focused around the effects of departing from Item P-401 Specifications for the standard 3/4 in. maximum aggregate size gradation and the percentage of crushed particles (coarse and fine) in the aggregate blend. The aggregate characterization tests were conducted to determine the effect of the shape of the aggregate gradation curve and to quantify the characteristics of the aggregate particle shape and texture. Analysis of these test results included a graphical analyses of the shape of the aggregate gradation curve with standard semi-log and 0.45 power maximum density gradation curves. The analysis also includes correlation of individual aggregate characterization tests with the percentage of crushed particles for composite (total), coarse, and fine fractions.

Aggregate Gradations

Fabricated test gradations were produced to determine the effects of variation from the 3/4 in. maximum aggregate gradation specified in Item P-401. The numerical values for the test gradations are presented in Table 6. Blends A-H were fabricated with crushed limestone materials so that the effect of gradation could be evaluated with high quality aggregates and the effects of particle shape would be minimized. These test gradations were designed to evaluate the general shape of the aggregate gradation curve as the gradations varied from inside and outside the maximum limits of the FAA specification. The selected test gradations also included poorly-graded blends. Blends I-M were fabricated with crushed gravel with various amounts of coarse natural sand materials. These test gradations were designed to evaluate the effect of the fine aggregate portion (minus No. 4 sieve) of the gradation curve.

Particle Shape and Texture

Aggregate particle characterization tests were conducted to quantify the shape and surface texture of the aggregates in each aggregate blend and to correlate these aggregate characteristics to the percentage of crushed coarse particles (Blends I, N-Q) and to the amount of natural sand (Blends I-M) in the aggregate blend. Currently, Item P-401 controls the quality of the aggregate shape and surface texture by specifying minimum values for

Table 6. Aggregate Gradations for HMA Mixtures

Aggregate blend	Sieve sizes (percent passing)									
	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
A	100	89.9	77.4	57.0	44.5	28.3	23.0	15.6	8.4	5.6
B	100	79.8	62.4	42.7	32.2	18.0	14.0	9.1	5.2	2.6
C	100	99.1	87.6	67.8	56.0	39.0	32.9	23.9	13.9	6.9
D	100	94.1	88.4	76.7	66.5	50.3	42.0	27.3	13.8	7.4
E	100	99.1	87.6	67.7	55.3	37.9	31.3	20.9	14.7	10.7
F	100	80.7	67.9	48.1	43.3	38.0	31.0	22.3	13.0	4.8
G	100	69.9	64.1	63.9	54.8	38.0	31.7	22.7	13.0	6.3
H	100	79.8	62.4	42.8	35.3	25.6	22.7	21.2	16.2	5.8
I	100	88.7	77.7	58.4	42.1	30.7	23.2	15.9	10.8	4.6
J	100	88.7	77.7	58.1	42.1	33.1	24.5	13.1	9.0	4.0
K	100	88.7	77.6	57.8	42.2	35.4	28.9	13.0	8.6	3.7
L	100	88.7	77.6	57.5	43.9	39.7	33.7	12.9	8.2	3.5
M	100	88.7	77.6	57.3	44.8	42.1	36.6	11.0	6.8	3.4
N	100	88.5	77.9	58.0	42.0	30.7	23.2	15.9	10.8	4.6

(Sheet 1 of 2)

Table 6. Aggregate Gradations for HMA Mixtures (Concluded)

Aggregate blend	Sieve sizes (percent passing)									
	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
O	100	88.5	77.9	58.0	42.0	30.7	23.2	15.9	10.8	4.6
P	100	88.5	77.9	58.0	42.0	30.7	23.2	15.9	10.8	4.6
Q	100	88.5	77.9	58.0	42.0	30.7	23.2	15.9	10.8	4.6
R	100	89.2	78.2	57.5	44.0	26.3	24.2	14.7	9.5	4.0
FAA limits	100	79-99	68-88	48-68	33-53	20-40	14-30	9-21	6-16	3-6

(Sheet 2 of 2)

crushed particles with 2 fractured faces (70 percent coarse and fine) and the maximum amount of natural sand (20 percent by total aggregate weight). The analysis also included a correlation of aggregate characterization tests to the Particle Index value which is a standardized test method for aggregate characterization for asphalt concrete mixtures.

Percent Crushed Particles. A crushed particle is defined as an aggregate particle that has at least two mechanically induced fractured faces. The labstock materials used to fabricate the test aggregate blends were crushed limestone, crushed gravel, uncrushed gravel, natural coarse sand and natural fine sand. Since each aggregate blend was fabricated with individual sieve sizes of each labstock material, the percentage of crushed particles for each aggregate blend was determined from the batch weight percentages. The percent crushed particle values and the natural sand content for each aggregate blend are listed in Table 7.

Particle Index. The Particle Index test (ASTM D 3398) is based on the concept that aggregate void characteristics for a one-sized aggregate compacted in a standard mold indicate aggregate shape, angularity, and surface texture. Numerous studies have indicated that the Particle Index value is larger for aggregates that are more irregular, angular, and rougher. These studies concluded that aggregates with rounded particles and smooth surface textures have a Particle Index of 6 to 7 or less, while aggregate with crushed particles and rough textures have a Particle Index of 15 to 20 or more. A Particle Index value of 14 has also been found to separate uncrushed natural sands from manufactured sands. (33,35,39)

Table 7. Percent Crushed Particles and Natural Sand Content

Aggregate blend	Percent crushed particles with at least 2 fractured faces			Natural sand content
	Composite gradation	Coarse aggregate fraction	Fine aggregate fraction	
A	100	100	100	0
B	92	100	75	8
C	88	100	79	12
D	91	100	86	9
E	90	100	82	10
F	90	100	77	10
G	88	100	78	12
H	85	100	58	15
I	98	97	100	0
J	88	97	76	10
K	78	97	53	20
L	68	97	32	30
M	58	97	11	40
N	81	68	100	0
O	70	49	100	0
P	58	29	100	0
Q	42	0	100	0
R	0	0	0	57.5

The Particle Index test was conducted on each size fraction of each labstock material. The Particle Index values for these labstock materials are presented in Table 8. The weighted Particle Index for each aggregate blend was calculated on the basis of the weight percentage of each size fraction in the aggregate gradation. The weighted Particle Index values for the composite gradation, coarse aggregate fraction, and fine aggregate fraction are listed in Table 9. To simplify and shorten this method, the Particle Index value was determined for the major sieve fraction and the major plus second major sieve fractions of the aggregate blend. These Particle Index values are also listed in Table 9.

Table 8. Particle Index Values for Labstock Materials

Size fraction	Crushed limestone	Crushed gravel	Uncrushed gravel
3/4 in. - 1/2 in.	15.0	12.8	8.7
1/2 in. - 3/8 in.	15.5	14.0	8.8
3/8 in. - No. 4	16.3	13.5	8.0
No. 4 - No. 8	17.2	15.6	8.8
No. 8 - No. 16	17.2	16.6	7.8
No. 16 - No. 30	15.9	16.6	-- *
No. 30 - No. 50	15.7	13.4	6.4
No. 50 - No. 100	14.7	14.2	9.7
No. 100 - No. 200	15.4	19.9	9.4
Fine aggregates			
Coarse natural sand	5.9		
Fine natural sand	9.0		
Limestone filler	16.0		

* Not used to fabricate test gradations.

Table 9. Particle Index Values for Aggregate Blends

Aggregate blend	Composite Particle Index	Coarse aggregate Particle Index	Fine aggregate Particle Index	Major fraction Particle Index	Major + 2nd major Particle Index
A	16.2	16.2	16.2	16.3	16.7
B	15.3	15.8	13.8	15.0	15.3
C	15.3	16.5	14.1	16.3	16.8
D	15.4	16.6	14.6	15.0	15.7
E	15.4	16.5	14.3	16.3	16.8
F	15.1	15.9	13.9	15.0	15.7
G	15.0	15.8	14.2	15.0	16.1
H	14.8	15.7	12.7	15.0	15.5
I	14.8	14.1	15.9	13.5	13.2
J	13.8	14.0	13.5	13.5	13.2
K	12.8	13.9	11.2	5.9	9.7
L	11.9	13.9	9.3	5.9	9.7
M	11.1	13.9	7.8	5.9	9.7
N	13.6	12.3	15.6	13.5	14.5
O	13.1	11.5	15.6	16.6	15.0
P	12.4	10.3	15.6	8.0	8.4
Q	11.3	8.5	15.6	8.0	8.4
R	8.3	8.4	8.1	8.0	7.9

NAA Particle Shape and Texture. This aggregate characterization test was developed as a simple routine test to measure the aggregate particle shape and surface texture using the loose uncompacted void content of a fine aggregate. Several studies concluded that decreasing aggregate angularity and smoother surface textures will decrease the loose uncompacted void content. These studies have found that this test method can distinguish the difference between aggregate shapes and surface textures of fine aggregate, but the three methods (A, B, C) produce different void levels for the same aggregate because of different aggregate gradings. (37,38,39)

For this laboratory study, Methods A and C were used to characterize each aggregate blend. Method A uses a standard fine aggregate grading of 190 grams that can be obtained from individual sieve fractions. The standard grading and weights were previously presented in Chapter IV. Method C uses 190 grams of as-prepared material that passes the No. 4 sieve. Conducting the flow test with this material was more difficult due to the clogging of the funnel by the plus No. 8 material. The clogging of the funnel interrupted the free flow of the fine aggregate through the funnel orifice. Slight tamping of the funnel was required to unclog the larger particles. The calculated uncompacted void contents for Methods A and C presented in Table 10 are an average of three replicants for each aggregate blend. The differences in aggregate blends N-Q (all crushed gravel) illustrate the variability in the test procedure and samples.

Modified NAA Particle Shape and Texture. The NAA particle shape and texture apparatus was modified and enlarged to test and evaluate larger coarser aggregate particles (No. 4 to 3/4 in.). This test apparatus was used to determine the shape and surface texture of coarse aggregate particles using the loose uncompacted void content. Since the concept of using void contents to characterize aggregate shape and surface texture had been successful with other test methods, enlarging the NAA flow test apparatus to quantify the coarse aggregate shape and texture seemed to be a valid and practical idea.

Table 10. NAA Particle Shape and Texture Values for Fine Aggregate

Aggregate blend	Method A	Method C
A	47.1	39.3
B	46.4	39.3
C	47.2	38.1
D	46.6	40.0
E	46.8	40.5
F	45.8	41.0
G	47.4	39.2
H	44.2	36.4
I	45.9	39.0
J	44.1	37.4
K	43.1	35.7
L	41.2	36.1
M	39.9	36.2
N	46.2	37.3
O	46.2	37.6
P	44.3	36.6
Q	45.9	37.6
R	38.4	33.4

Since there was no established procedure for testing coarse aggregate in this manner, a method similar to the fine aggregate test method was used. This method uses the as-prepared material that passed the 3/4 in. sieve but was retained on the No. 4 sieve to determine the uncompacted void content of the coarse aggregate. The calculated uncompacted void contents for the modified NAA test apparatus presented in Table 11 are an average of five replicants.

Table 11. Uncompacted Void Contents for Coarse Aggregate using Modified NAA Test Apparatus

Aggregate blend	As-prepared material
A	47.0
B	46.4
C	47.4
D	47.4
E	47.7
F	46.4
G	49.1
H	46.8
I	45.9
J	45.9
K	45.9
L	45.9
M	45.9
N	43.7
O	42.9
P	41.6
Q	40.3
R	39.9

Direct Shear. The direct shear test was used to determine the angle of internal friction of the fine aggregate for each aggregate blend. Theoretically, this test method should produce a valid relationship between the angle of internal friction and the aggregate shape and surface texture, but conflicting results have been reported. Winford (39) reported that the angle of internal friction values separated the natural sand materials from the manufactured sand materials while Stuart (40,41) concluded that the direct shear method was not a good indicator of sand shape and texture.

The direct shear test was conducted on the minus No. 4 sieve material of each aggregate blend. The test was conducted using three normal stress levels, 14 psi, 28 psi, and 42 psi. The angle of internal friction was determined by plotting shear stress versus normal stress and analytically determining the angle produced by the "best fit" line through the data points. The angle of internal friction values for each aggregate blend are presented in Table 12.

Unit Weight and Voids in Aggregate. This test method (ASTM C 29) is used to determine the unit weight and void content in an aggregate matrix for fine, coarse, and mixed aggregate blends. The unit weight and void content can be calculated in a loose or compacted condition. This test procedure was developed to select proportions for concrete mixtures, but the determination of void contents in an aggregate matrix has been proven to be a valid method of characterizing aggregate particle shape and surface texture.

Table 12. Angle of Internal Friction Values for Fine Aggregate

Aggregate blend	Angle of internal friction
A	42.5
B	46.0
C	41.5
D	42.0
E	42.5
F	41.5
G	41.0
H	40.5
I	41.5
J	41.0
K	39.0
L	40.5
M	36.5
N	43.5
O	42.5
P	41.5
Q	42.5
R	39.5

For this laboratory study, the coarse aggregate fraction of each aggregate blend was tested. The rodding procedure which produces a compacted sample and the shoveling procedure which produces a loose sample were used to evaluate the shape and surface texture characteristics of the coarse aggregate fraction. The void content was determined for the as-prepared fractions of each blend. The calculated void contents for the coarse aggregate fraction are presented in Table 13.

Table 13. Void Contents for Coarse Aggregate from ASTM C 29 Method

Aggregate blend	Rodding procedure	Shoveling procedure
	As-prepared material	As-prepared material
A	41.3	45.9
B	41.3	46.0
C	42.1	46.3
D	41.2	46.3
E	41.2	46.4
F	41.2	45.7
G	43.6	48.8
H	41.0	45.8
I	40.7	44.6
J	40.7	44.6
K	40.7	44.6
L	40.7	44.6
M	40.7	44.6
N	38.5	42.5
O	37.8	41.9
P	37.3	40.8
Q	35.4	38.6
R	35.9	38.6

Analysis and Discussion of Test Results

Aggregate Gradations

Graphical analysis of an aggregate gradation is the best way to evaluate a gradation curve if asphalt concrete mixture data or field performance data are not available. The graphical analysis involves plotting the gradation curve against proven specification bands or plotting the gradation curve on a 0.45 power maximum density gradation curve. Comparison of the test gradation to these established specifications is an indicator of relative performance but not an absolute predictor of asphalt concrete performance.

Of the fourteen test gradations designed to evaluate the aggregate gradation characteristics of asphalt concrete mixture, only five aggregate blends (Mixes A, I, J, K, and R) would fall inside the specified FAA limits listed in Table 6. This means the other nine aggregate blends would be classified as substandard aggregate blends. The aggregate gradations are plotted with the FAA specification limits on standard semi-log gradation curves in Figures 15-18.

Previous research studies have indicated that plotting aggregate gradations with a 0.45 power maximum density gradation curve can indicate the quality of the aggregate blend. (7,8,9) Aggregate gradations that produce a hump between the No. 4 and No. 100 sieve sizes generally produce a tender or unstable asphalt concrete mixture. This hump is generally around the No. 30 sieve and is generally produced by an excess amount of middle-sized natural sand particles.

This hump was evident in several aggregate gradations fabricated for this laboratory study (Mixes K, L, M, and R). As the percentage of natural sand material increased, the hump at the No. 30 sieve increased. Based on previous laboratory and field studies, these aggregate blends should produce sensitive, tender asphalt concrete mixtures. (27,52) The aggregate gradation curves are plotted with the 0.45 power maximum density line in Figures 19-22. The evaluation and analysis of the effect of the general shape of an aggregate gradation can best be conducted by comparing the gradations with the HMA properties.

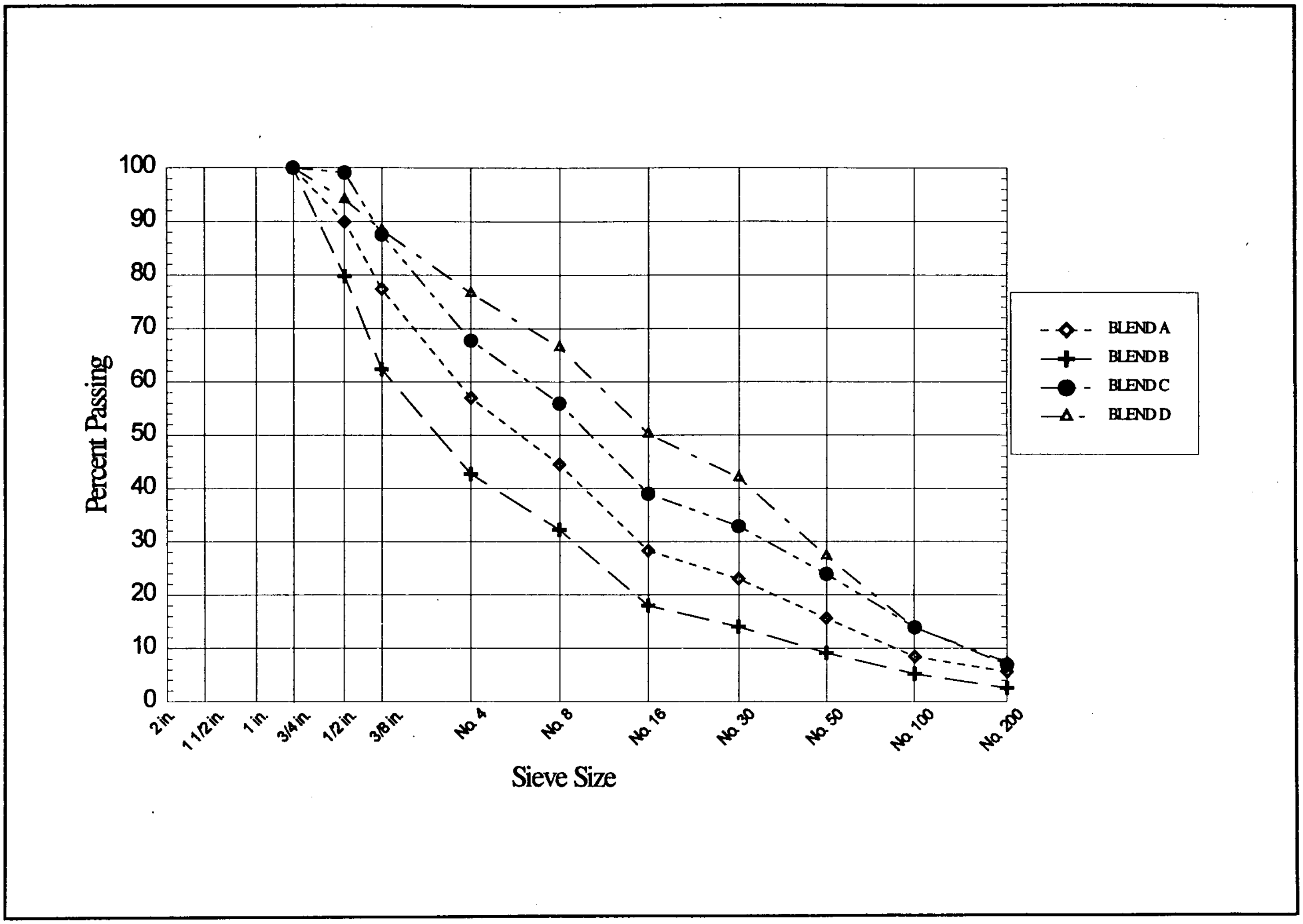


Figure 15. Gradation Curves for Aggregate Blends A-D

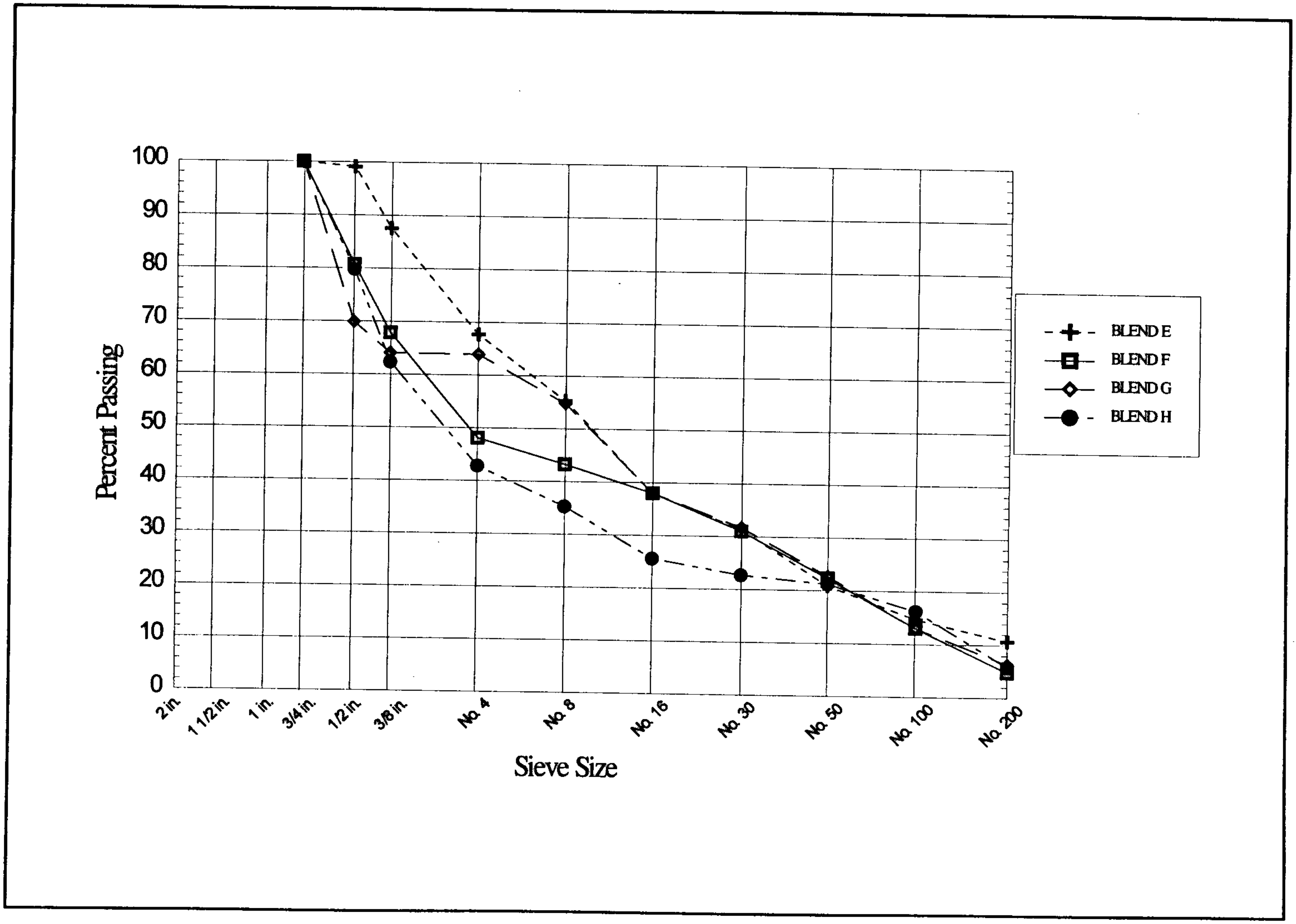


Figure 16. Gradation Curves for Aggregate Blends E-H

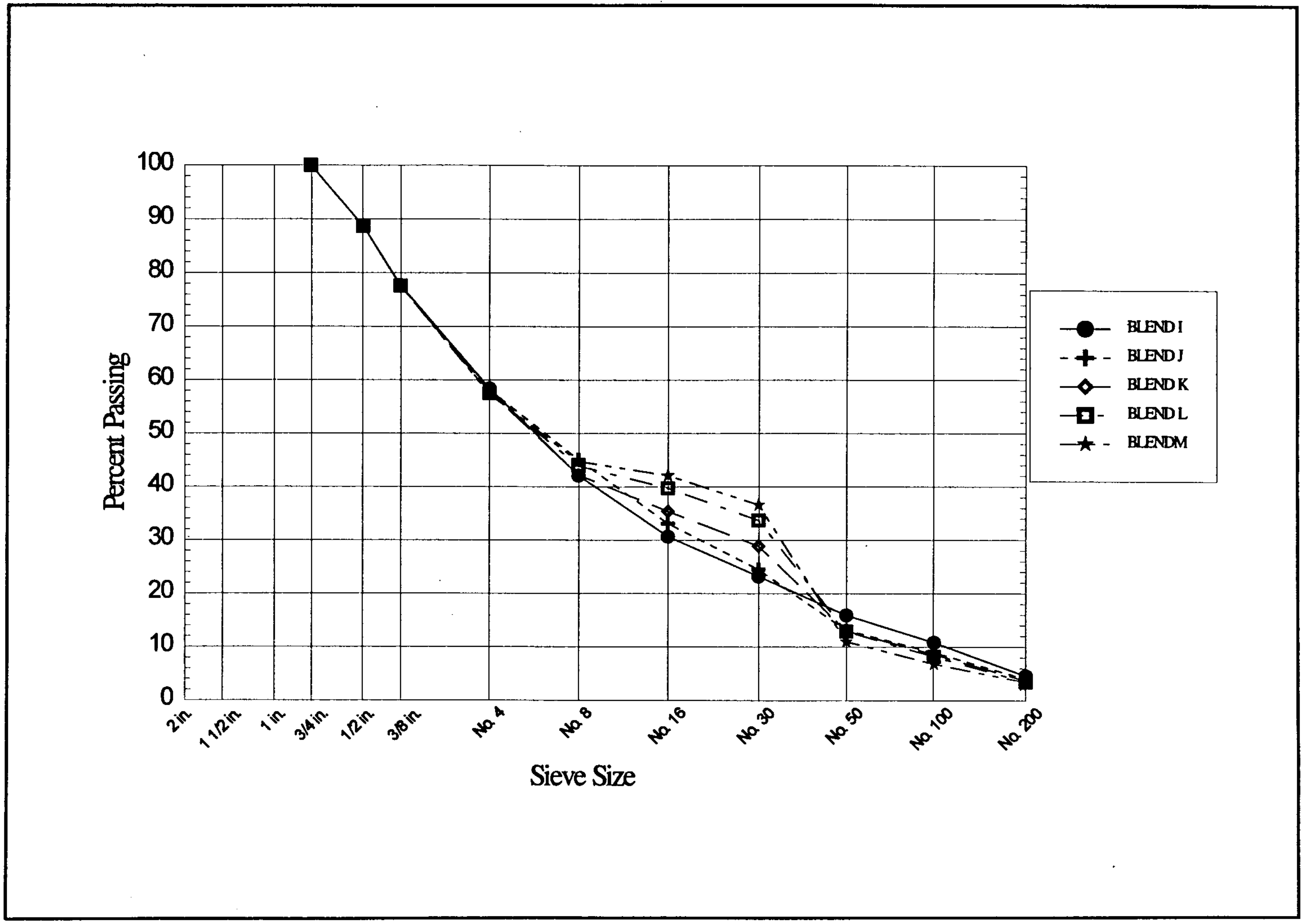


Figure 17. Gradation Curves for Aggregate Blends I-M

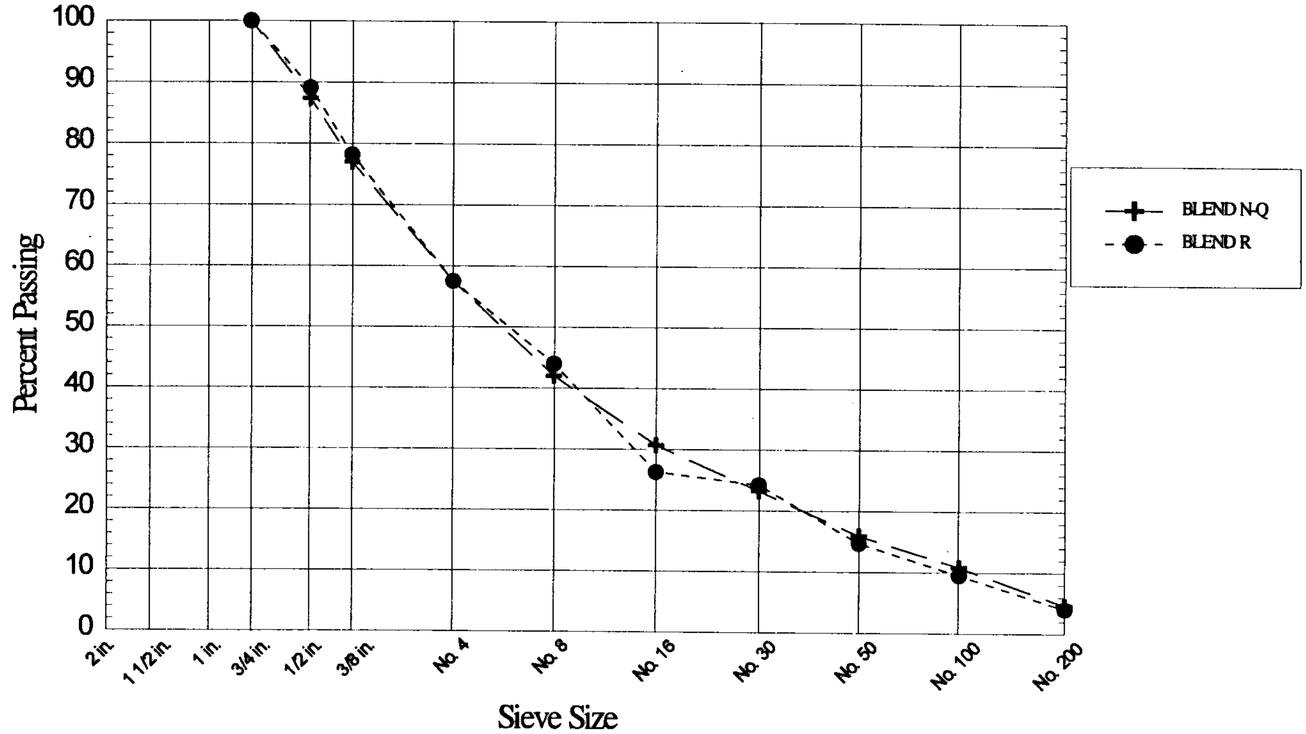


Figure 18. Gradation Curves for Aggregate Blends N-R

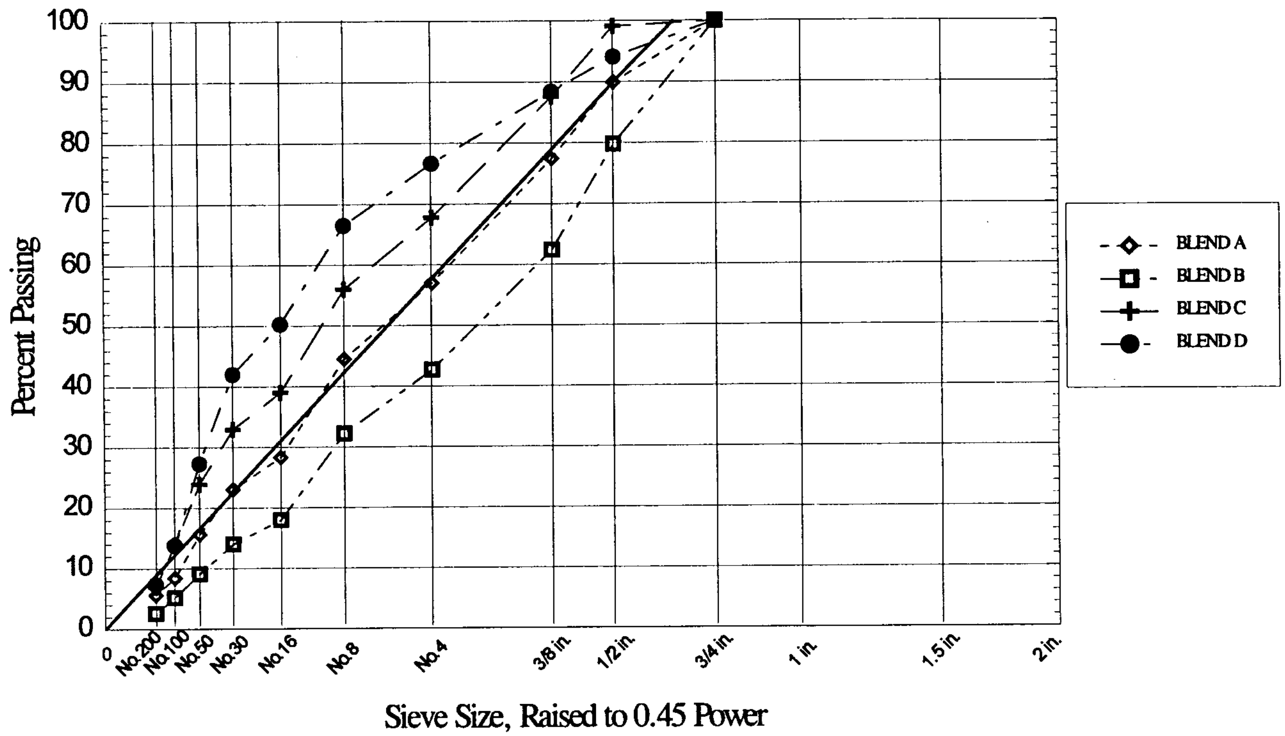


Figure 19. 0.45 Power Gradation Curve - Blends A-D

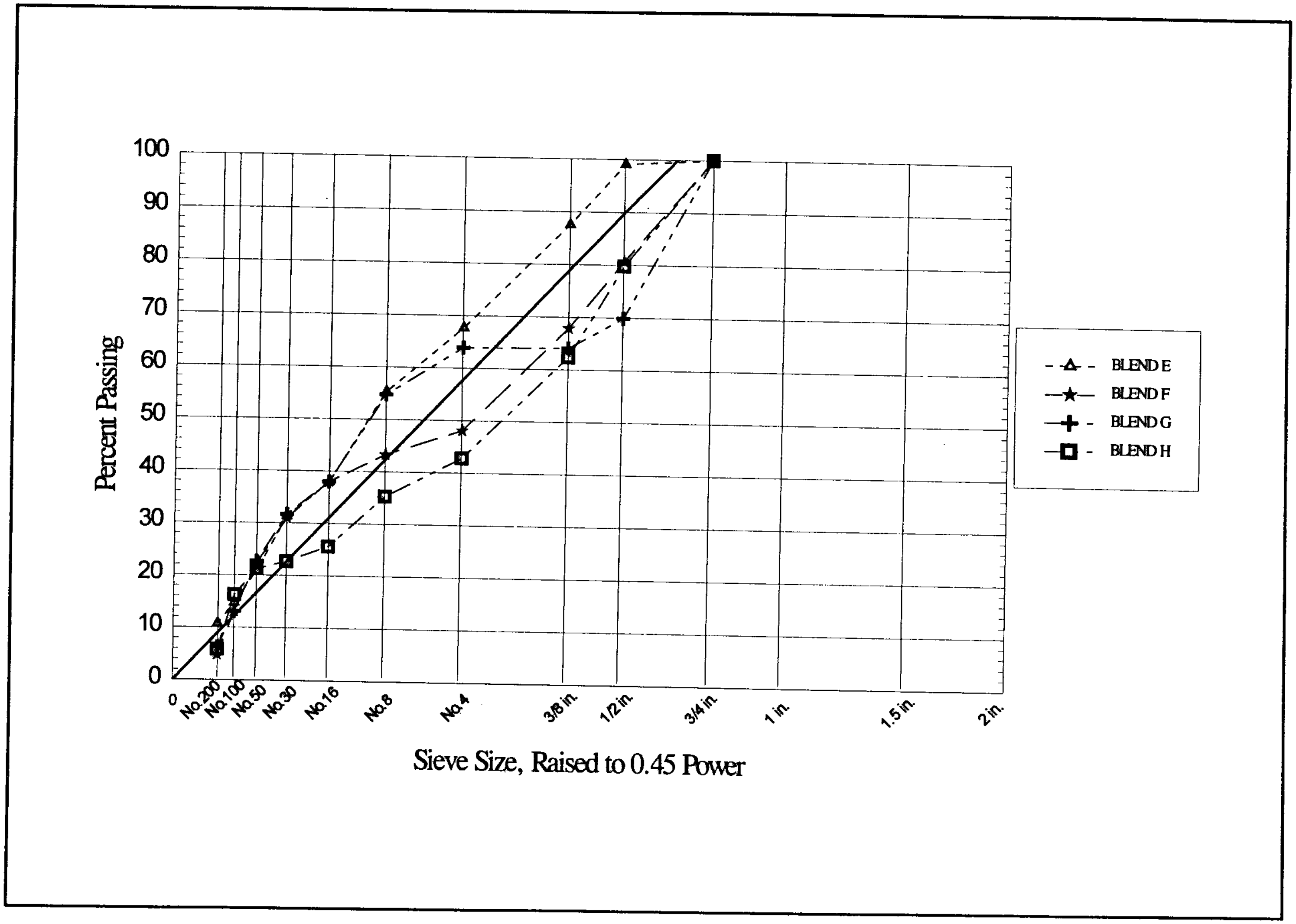


Figure 20. 0.45 Power Gradation Curve - Blends E-H

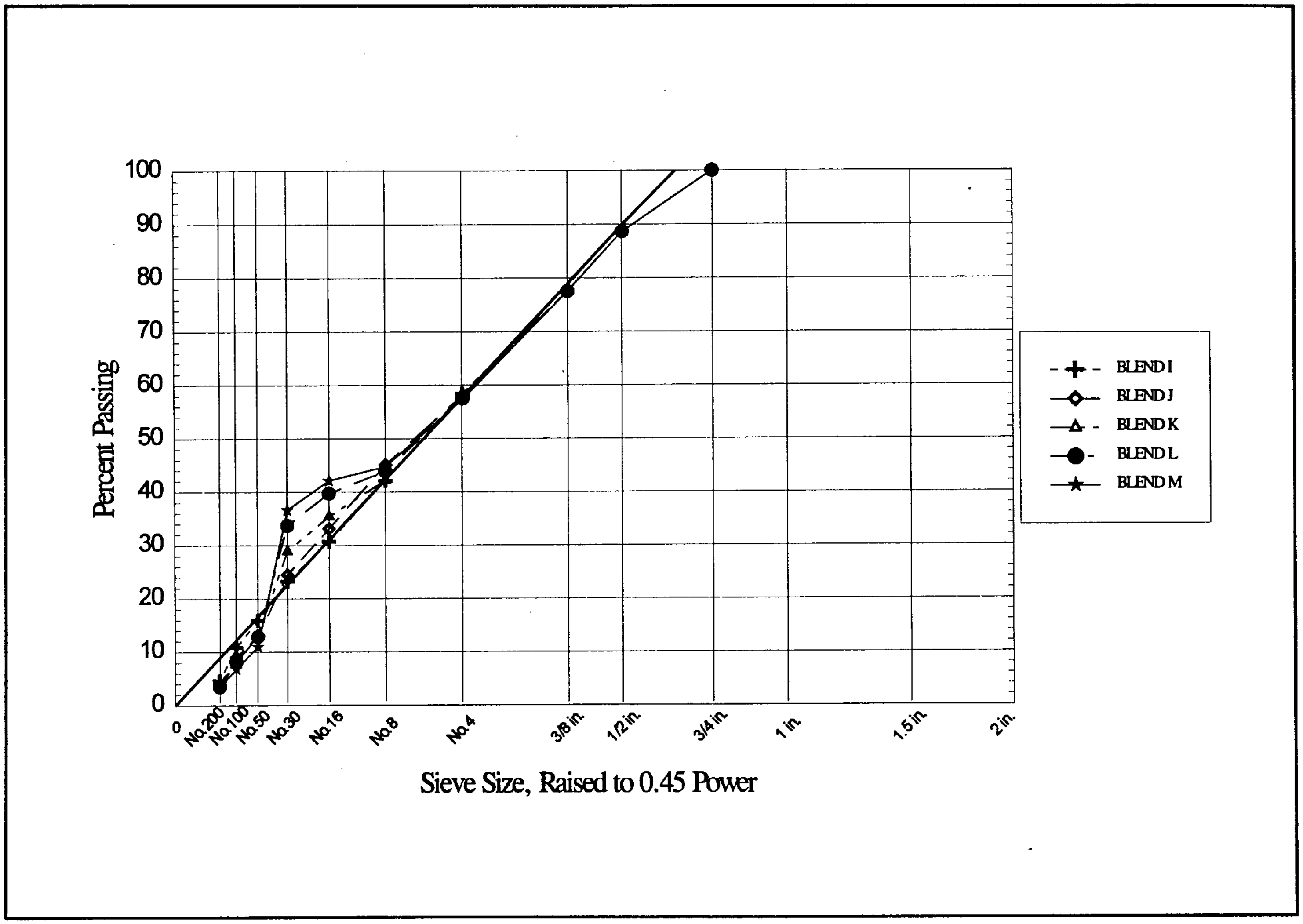


Figure 21. 0.45 Power Gradation Curve - Blends I-M

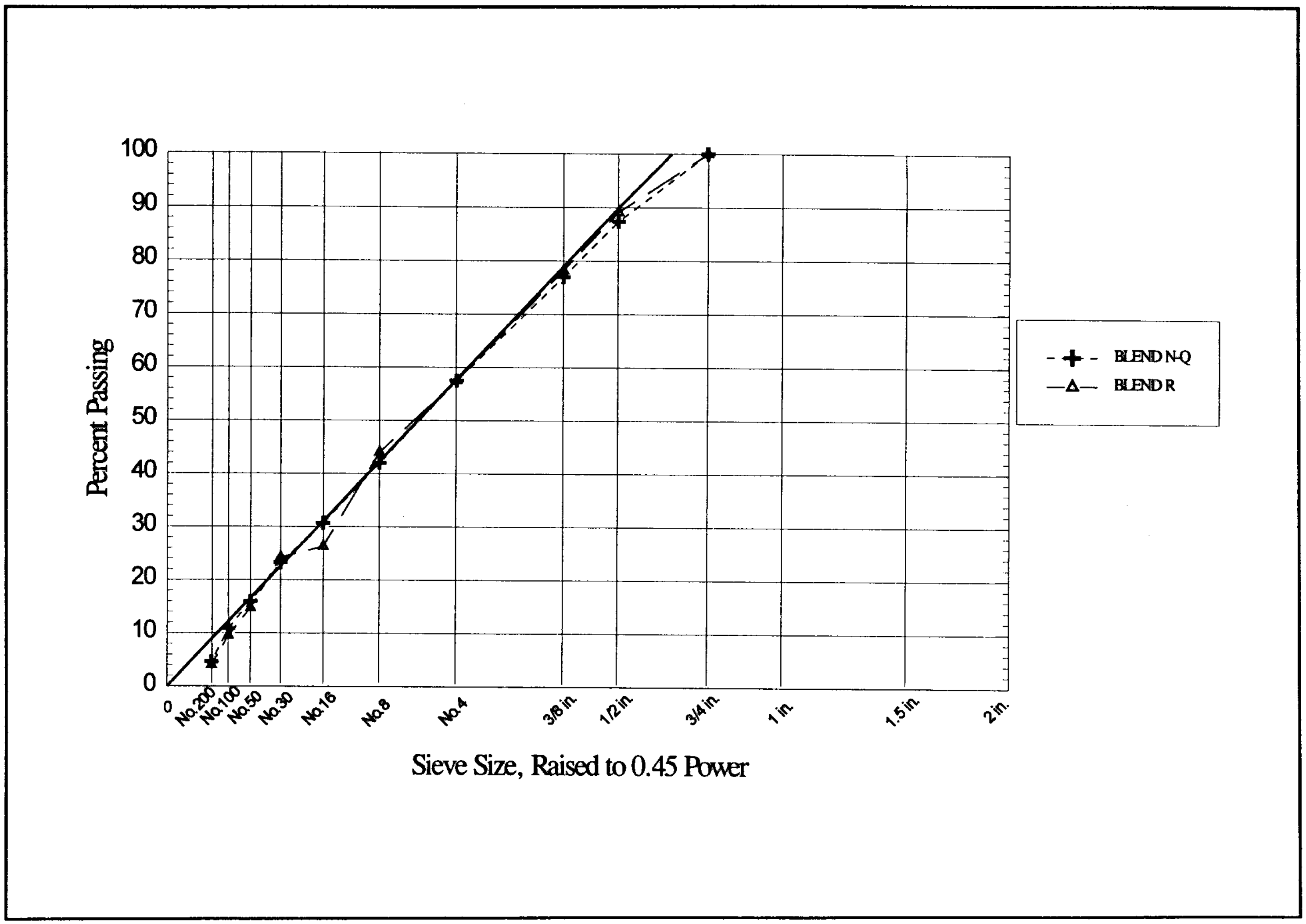


Figure 22. 0.45 Power Gradation Curve - Blends N-R

Particle Shape and Texture

The aggregate particle characterization tests were conducted to characterize and quantify the particle shape and surface texture of the aggregates in each aggregate blend. The analysis of these aggregate tests consisted of correlations of test results from the composite blend, coarse aggregate fraction and fine aggregate fraction with the percentage of crushed particles in the aggregate blends (Blends A-R). The analysis also included a correlation of the test results for the fine aggregate fractions with the amount of natural sand material in the aggregate blend (Blends I-M). The final correlation of the aggregate tests involved the non-standard aggregate tests with the Particle Index test results. These correlations were conducted to determine if aggregate tests could be used to improve aggregate specifications by replacing the current requirements of percent crushed particles for the coarse and fine aggregate fractions and the maximum limits for natural sand materials.

Correlation of Aggregate Characterization Tests with Percent Crushed Particles

1. The Particle Index test (ASTM D 3398) has been used in several laboratory studies to evaluate the particle shape and surface texture of aggregates. This method is effective in characterizing aggregate shape and texture but is tedious, time-consuming, and has been used primarily as a research tool. A summary of these previous studies indicates that angular, rough aggregates have a Particle Index value greater than 14 while round, smooth aggregates have a Particle Index value less than 12. The test results from this laboratory study (Table 9) agree with the findings in the literature. Mix A (crushed limestone) and Mix I (crushed gravel) had Particle Index values of 16.2 and 14.8, respectively, while Mix R (uncrushed gravel) had a Particle Index value of 8.3.

Correlations between the Particle Index values for the composite blend, coarse aggregate fraction, and fine aggregate fraction and the percent crushed particles for each fraction were conducted using linear regression. The coefficient of determination (R^2) was used to determine how strong the correlation was between the data points and the regression equation. A strong correlation or relationship was found between the Particle Index values and the percent crushed particles. The results of these correlations are shown in Figure 23. The R^2 values for these correlations were extremely high (0.870-composite, 0.866-coarse, 0.980-fine) and indicate there is a strong linear relationship between Particle Index values and the percent of crushed particles in an aggregate blend.

In order to shorten this time-consuming test procedure, correlations were conducted between Particle Index values for the major sieve size fraction and the major fraction plus the 2nd major sieve size fractions of the aggregate blends and the percent crushed particles. These correlations were not as strong as with the weighted composite Particle Index values. The R^2 value for the major sieve fraction of the aggregate blends was 0.396 while the R^2 value for the major plus 2nd major sieve fraction of the aggregate blends was 0.583. These results indicate that several sieve size fractions are required to produce as strong a correlation as did the weighted composite Particle Index values.

2. The modified NAA particle shape and texture test was used to characterize aggregate shape and texture of coarse aggregates using the loose uncompacted void content. The uncompacted void contents for this test method are presented in Table 11.

A strong correlation was determined for the uncompacted void contents determined using this modified NAA method and the percent crushed particles. The results of these correlations are shown in Figure 24. The R^2 value for the as-prepared samples is 0.891. This test method is an excellent indicator for crushed coarse particles.

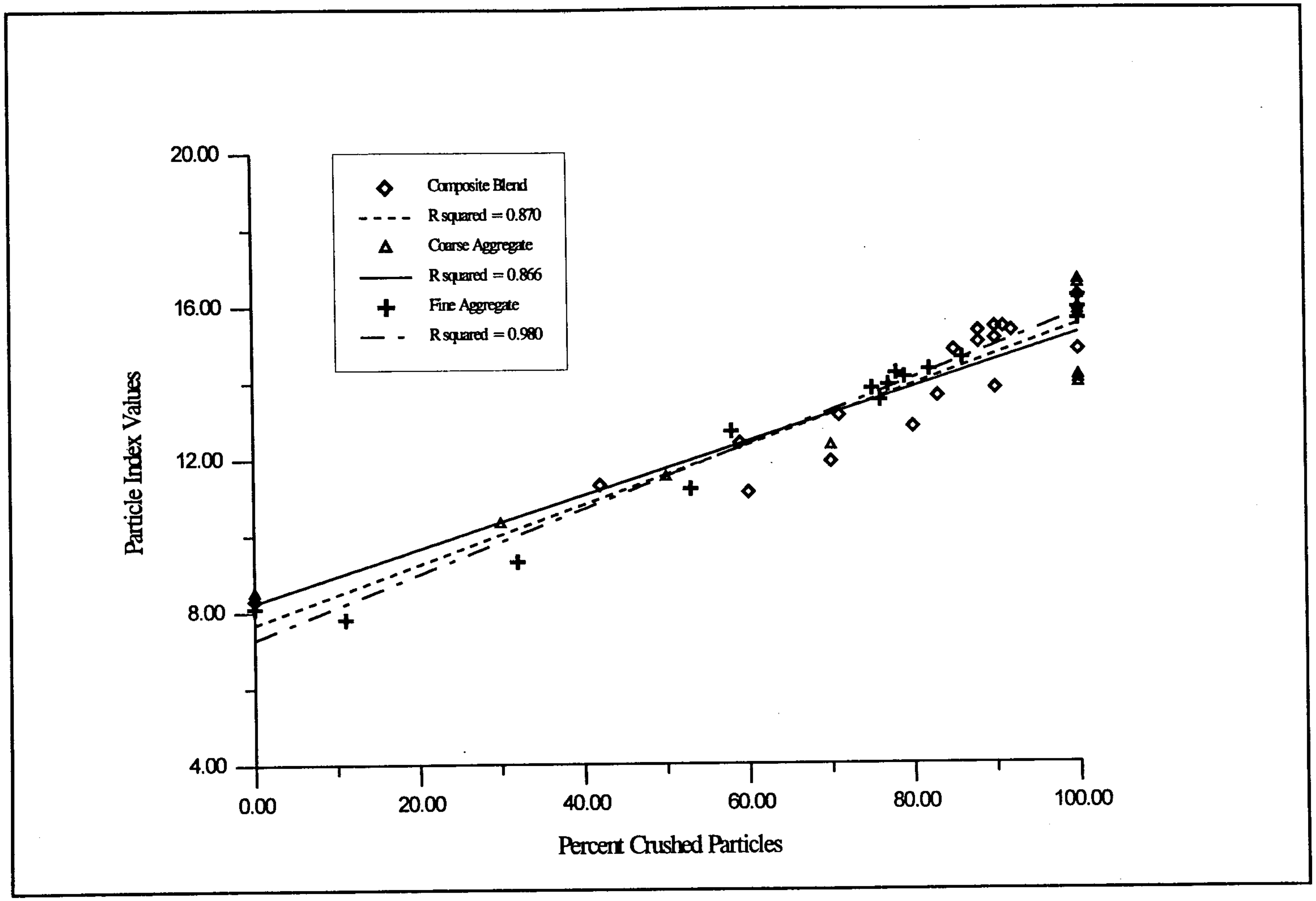


Figure 23. Particle Index Values versus Percent Crushed Particles for Composite Blend, Coarse and Fine Aggregate Fractions

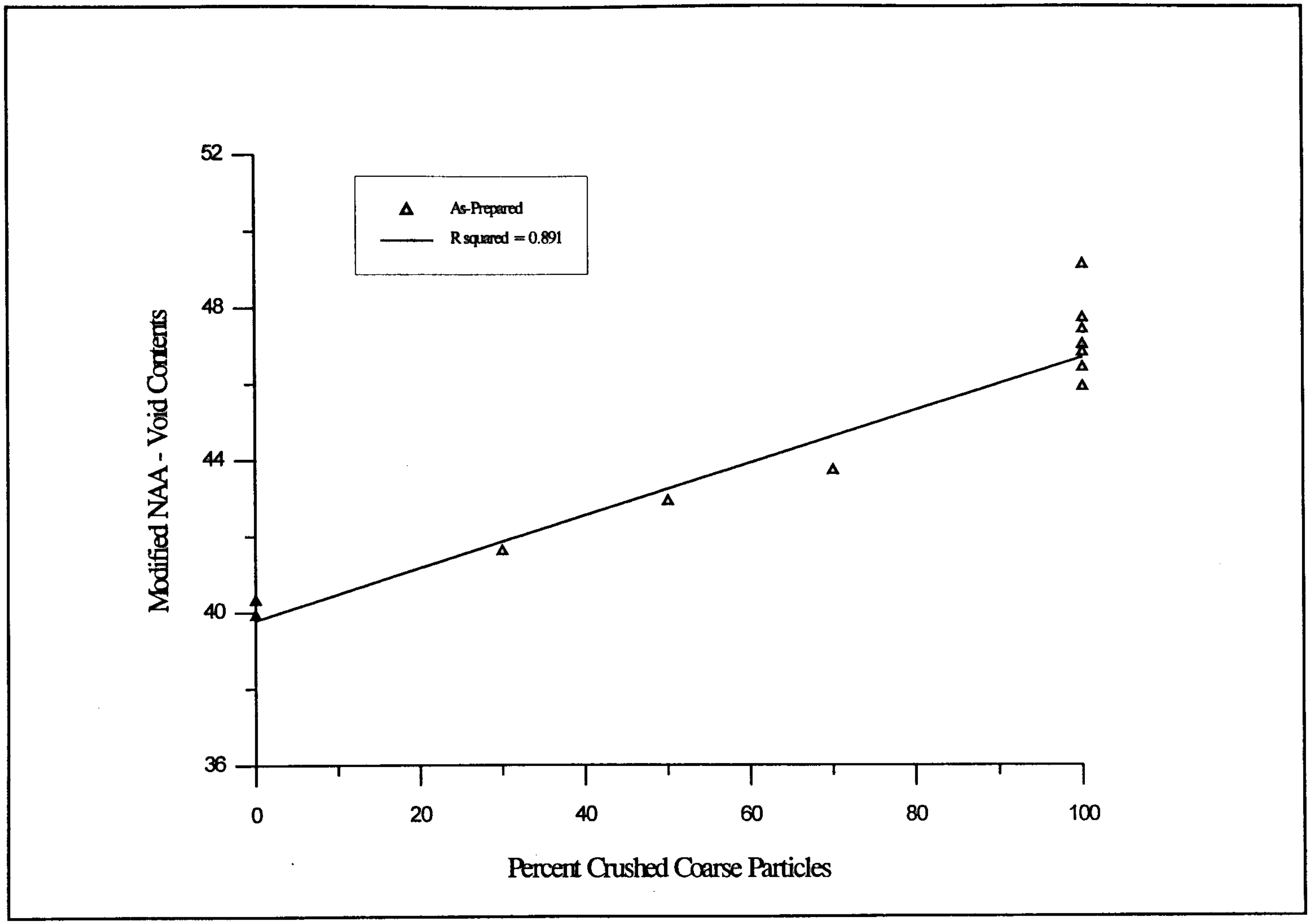


Figure 24. Modified NAA Particle Shape and Texture Void Contents versus Percent Crushed Coarse Particles

3. The unit weight and voids in aggregate test method (ASTM C 29) is primarily used for concrete mixture designs but because this method determines void contents of aggregates, this method was evaluated as an aggregate characterization test for the coarse aggregate fraction. The rodding procedure which produces a compacted sample and the shoveling procedure which produces a loose sample were used to evaluate the coarse aggregate shape characteristics. The uncompacted void contents for each procedure are presented in Table 13. As expected, the rodding procedure produced void contents approximately 4 percent lower than the shoveling procedure.

A correlation was determined for the uncompacted void contents determined using the rodding and shoveling procedures and the percent crushed coarse aggregate particles. The results of these correlations are shown in Figure 25. The R^2 value for the rodding procedure with as-prepared materials is 0.885. The R^2 values for the shoveling procedure with as-prepared materials is 0.859. These results indicate that either procedure (rodding or shoveling) could be used to determine the percent of crushed coarse particles in an aggregate blend.

4. The NAA particle shape and texture test method was used to measure the fine aggregate particle shape and surface texture using uncompacted void contents. Methods A and C were used in this laboratory evaluation and the results are presented in Table 10. The computed void contents for Method A are 4 to 8 percent higher than Method C void contents for the same aggregate blend. The difference between these results is due to the difference in aggregate grading. Method C is the as-received material which contains more fine material than Method A.

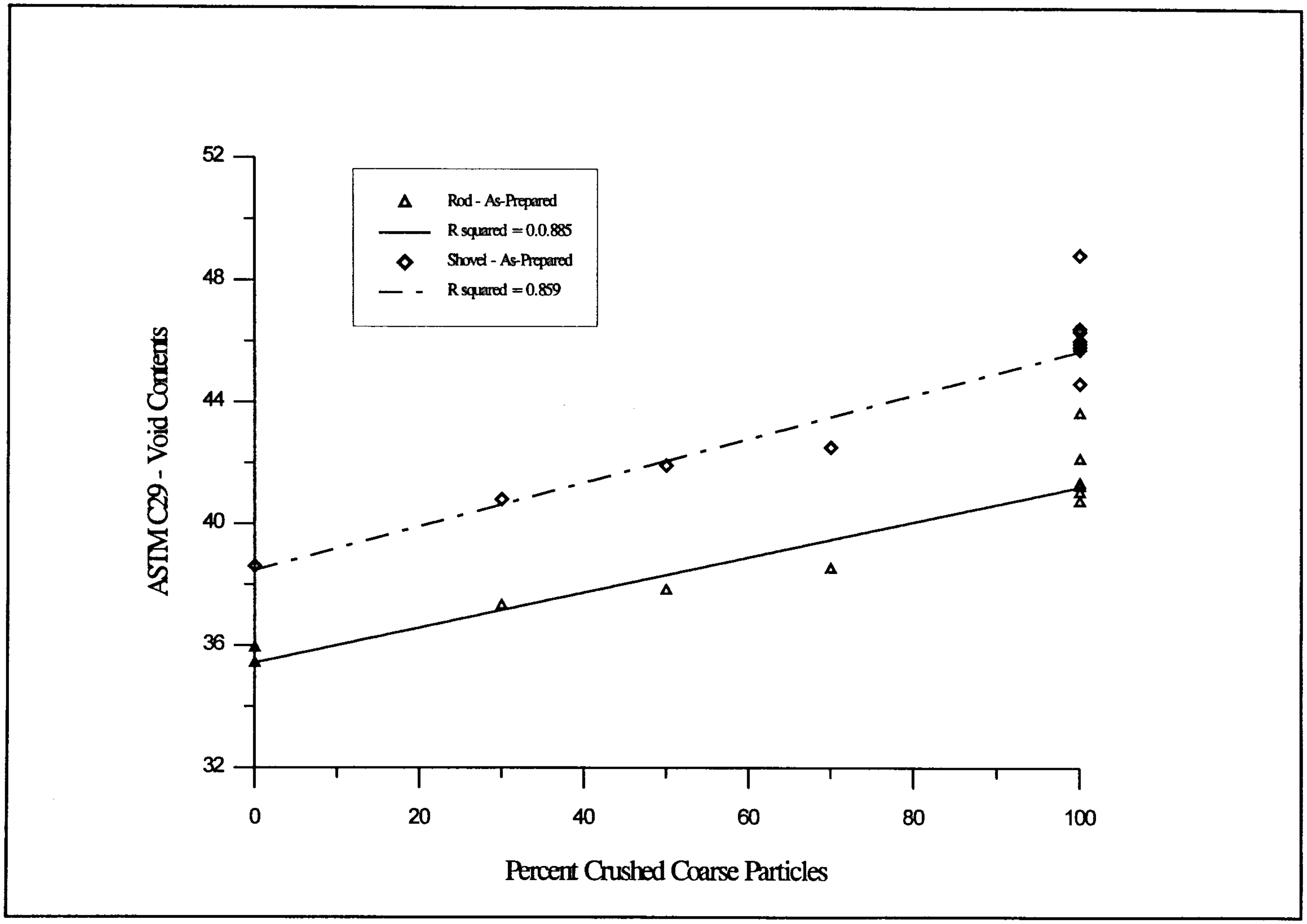


Figure 25. Void Contents from ASTM C 29 Method versus Percent Crushed Coarse Particles

The Method A test procedure has been used by several researchers to characterize fine aggregate shape and texture. A review of these recent studies indicated that angular, rough, fine aggregate have void contents greater than 45 and round, smooth, fine aggregate have void contents below 43. The test results from this laboratory study agree with the test results presented in the literature. Mix A (crushed limestone) and Mix I (crushed gravel) had void contents of 47.1 and 45.9, respectively, while Mix R (uncrushed gravel) had a void content of 38.4.

The correlations for void contents determined using NAA Methods A and C with percent crushed fine particles are shown in Figure 26. The correlation for Method C ($R^2 = 0.406$) was not as strong as the correlation for Method A ($R^2 = 0.788$). Based on this data, Method A (standard grading) is a better indicator of percent crushed fine particles than Method C (as-prepared material).

5. The direct shear test was conducted to determine the angle of internal friction (ϕ) of the fine aggregate. Theoretically, this method should produce a relationship between aggregate shape and texture and the angle of internal friction. A review of the literature produced conflicting results about the ability of this method to produce a strong relationship between aggregate shape and texture and the angle of internal friction. The test results for the minus No. 4 sieve material of each aggregate blend are presented in Table 12.

The correlation for angle of internal friction and percent crushed fine particles was not as strong as the previous aggregate characterization tests. The correlation for the direct shear test is shown in Figure 27. The R^2 value for this correlation was 0.480, the lowest for any test method. This low correlation is probably due to inconsistent densities of the samples which overshadowed the shape effects.

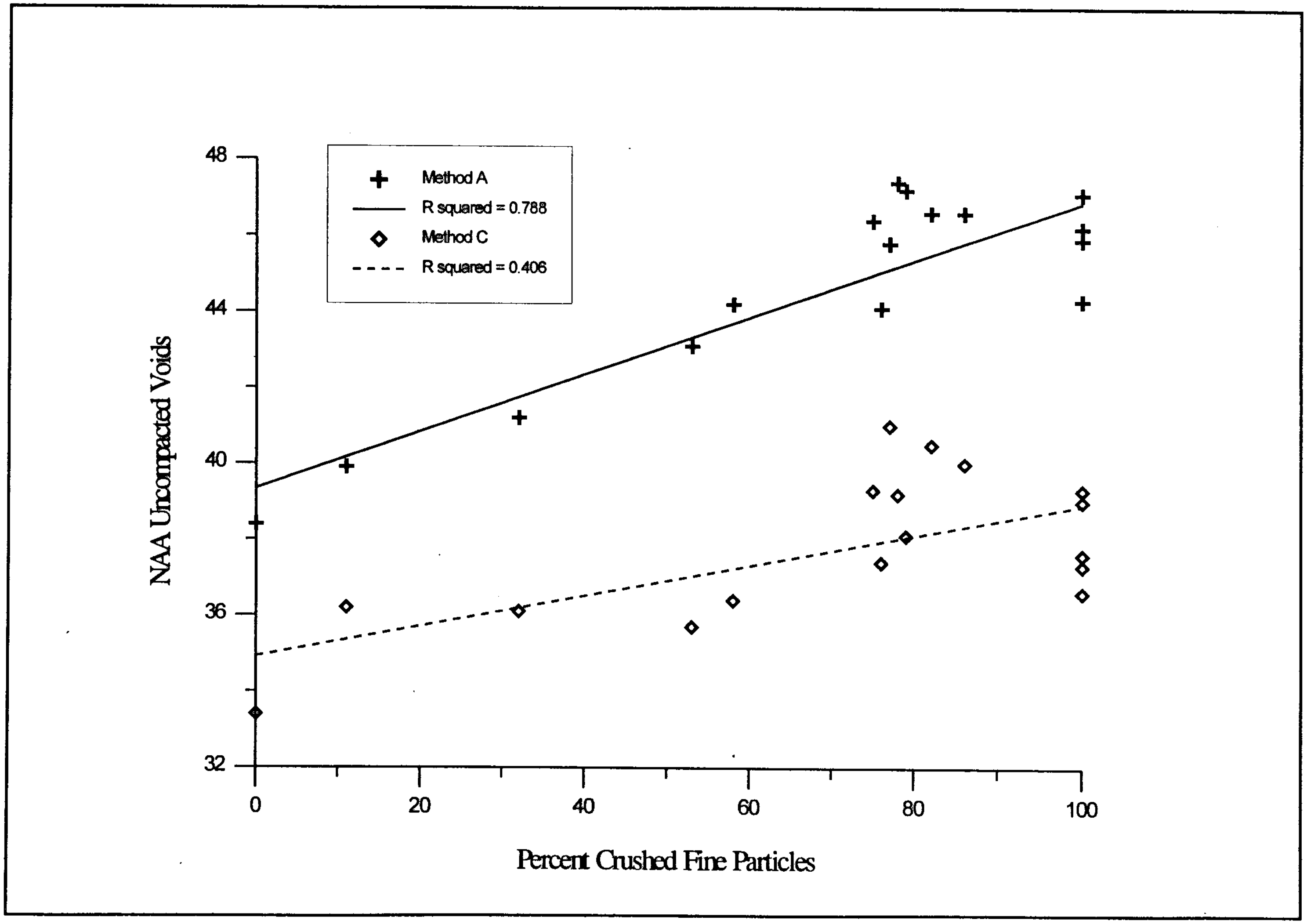


Figure 26. NAA Particle Shape and Texture Void Contents versus Percent Crushed Fine Particles

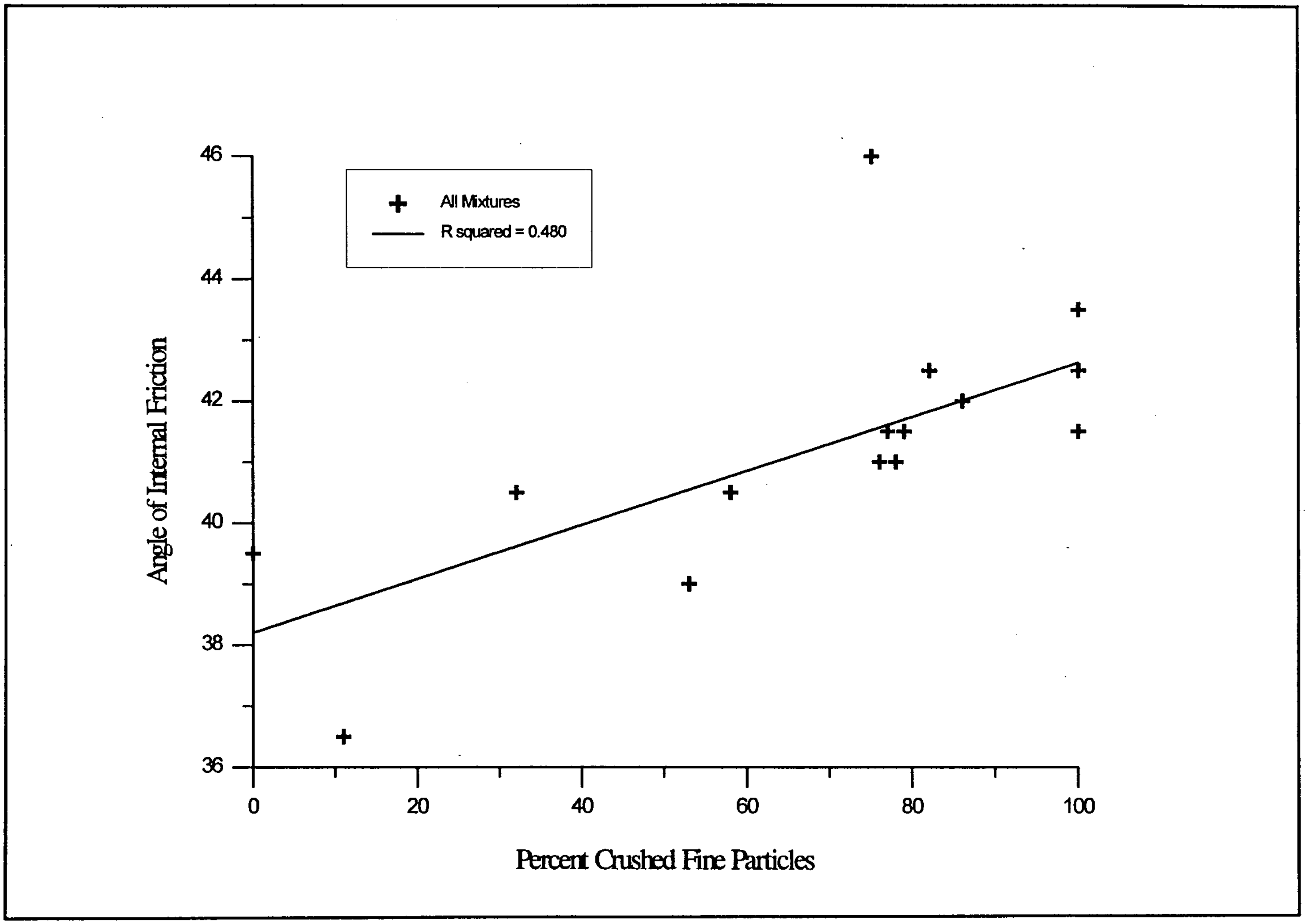


Figure 27. Angle of Internal Friction from Direct Shear Test versus Percent Crushed Fine Particles

6. A summary of coefficients of determination for the aggregate particle characterization tests and percent crushed particles is presented in Table 14. The Particle Index test produced extremely high correlations with percent crushed particles for composite blends, coarse aggregate fractions, and fine aggregate fractions. The idea of shortening the test procedure to one or two aggregate sizes did not produce good correlations. The Modified NAA test and ASTM C 29 both did an excellent job correlating void contents with percent crushed coarse aggregate. The NAA particle shape and texture test produced a very good correlation with percent crushed fine aggregate. The direct shear test produced the worst correlation of any aggregate characterization test with percent crushed particles. Based on this data, the Particle Index test, NAA particle shape and texture, Modified NAA test and ASTM C 29 methods would be viable alternatives to characterize aggregate shape instead of percent crushed particles.

Correlation of Fine Aggregate Characterization Tests with Natural Sand Content

1. A strong correlation was determined for the Particle Index value (fine aggregate) and the amount of natural sand in the fine aggregate. The result of this correlation is shown in Figure 28. The R^2 value for this linear correlation was 0.886. This correlation is approximately the same as the Particle Index correlation with percent crushed fine aggregate. The Particle Index test is an excellent indicator of the amount of natural sand in the aggregate blend.

Table 14. Correlation of Aggregate Particle Characterization Tests with Percent Crushed Particles

Aggregate size	Aggregate particle characterization test	Coefficient of determination (R^2)
Composite Blend	Particle Index	0.870
	Major Fraction Particle Index Value	0.396
	Major plus 2nd Major Fraction Particle Index Value	0.583
Coarse Aggregate	Particle Index	0.866
	Modified NAA, As-Prepared	0.891
	ASTM C 29 (Rod), As-Prepared	0.885
	ASTM C 29 (Shovel), As-Prepared	0.859
Fine Aggregate	Particle Index	0.980
	NAA, Method A	0.788
	NAA, Method C	0.406
	Direct Shear	0.480

2. The NAA particle shape and texture test was developed originally to measure the aggregate shape and texture of sand-sized materials. Several laboratory studies have evaluated this test method and found it can distinguish between round, smooth aggregates and angular, rough aggregates. An uncompacted void content of 44 to 45 is the separation of natural and manufactured sands for Method A. The test results from this study indicate that as the amount of natural sand increases the void contents decrease.

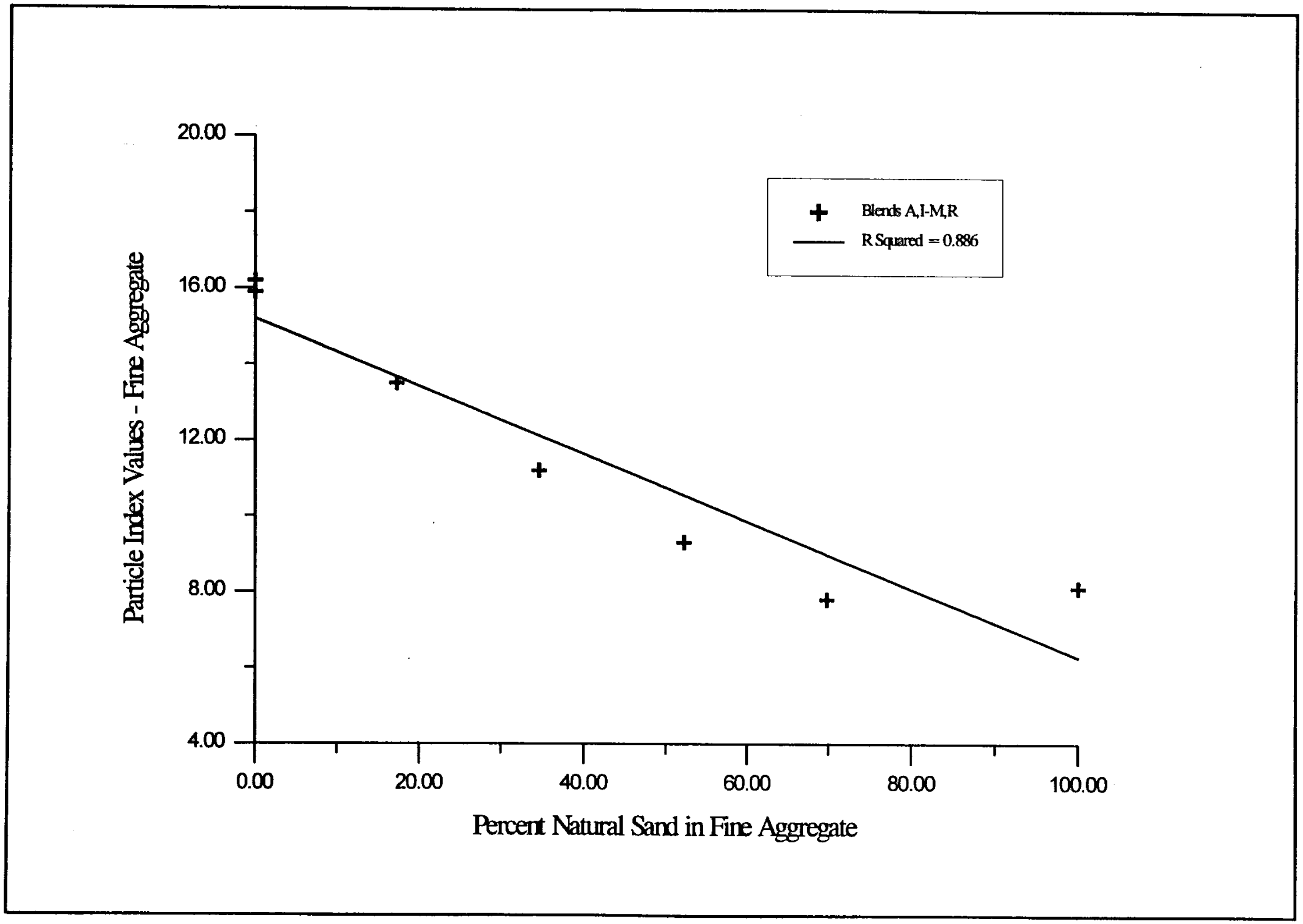


Figure 28. Particle Index Values versus Percent Natural Sand in Fine Aggregate

The correlations for void contents determined using NAA Methods A and C with the natural sand content are shown in Figure 29. The correlation for Method A is strong ($R^2 = 0.963$) while the correlation for Method C is slightly weaker ($R^2 = 0.868$).

3. As previously reported, the direct shear test should produce a relationship between aggregate shape and texture and angle of internal friction but fails to do so in many cases. The correlation of angle of internal friction to natural sand content is not very strong with a $R^2 = 0.479$. This correlation is shown in Figure 30.

4. A summary of coefficients of determination for fine aggregate particle characterization tests and the percent natural sand in the fine aggregate is presented in Table 15. The Particle Index test produced a correlation with natural sand which corresponds to the strong correlation the Particle Index test had with percent crushed fine particles. NAA Methods A and C produced good correlations with percent natural sand in the fine aggregates. The direct shear test produced an average correlation with natural sand content but was not as effective as the Particle Index and NAA particle shape and texture tests.

Table 15. Correlation of Fine Aggregate Particle Characterization Tests with Natural Sand Content

Fine aggregate particle characterization test	Coefficient of determination (R^2)
Particle Index	0.886
NAA - Method A	0.963
NAA - Method C	0.868
Direct Shear	0.479

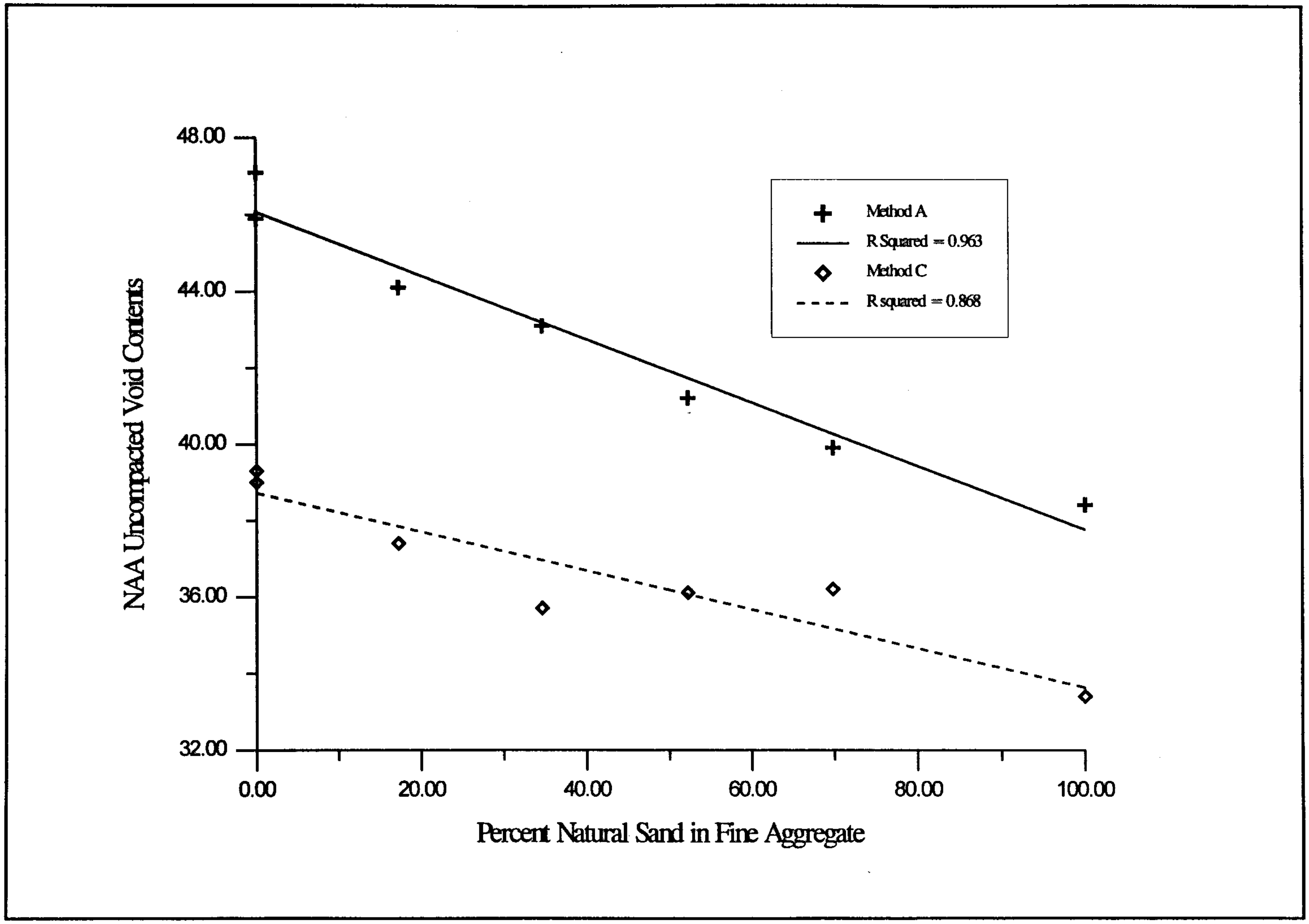


Figure 29. NAA Particle Shape and Texture Void Contents versus Percent Natural Sand in Fine Aggregate

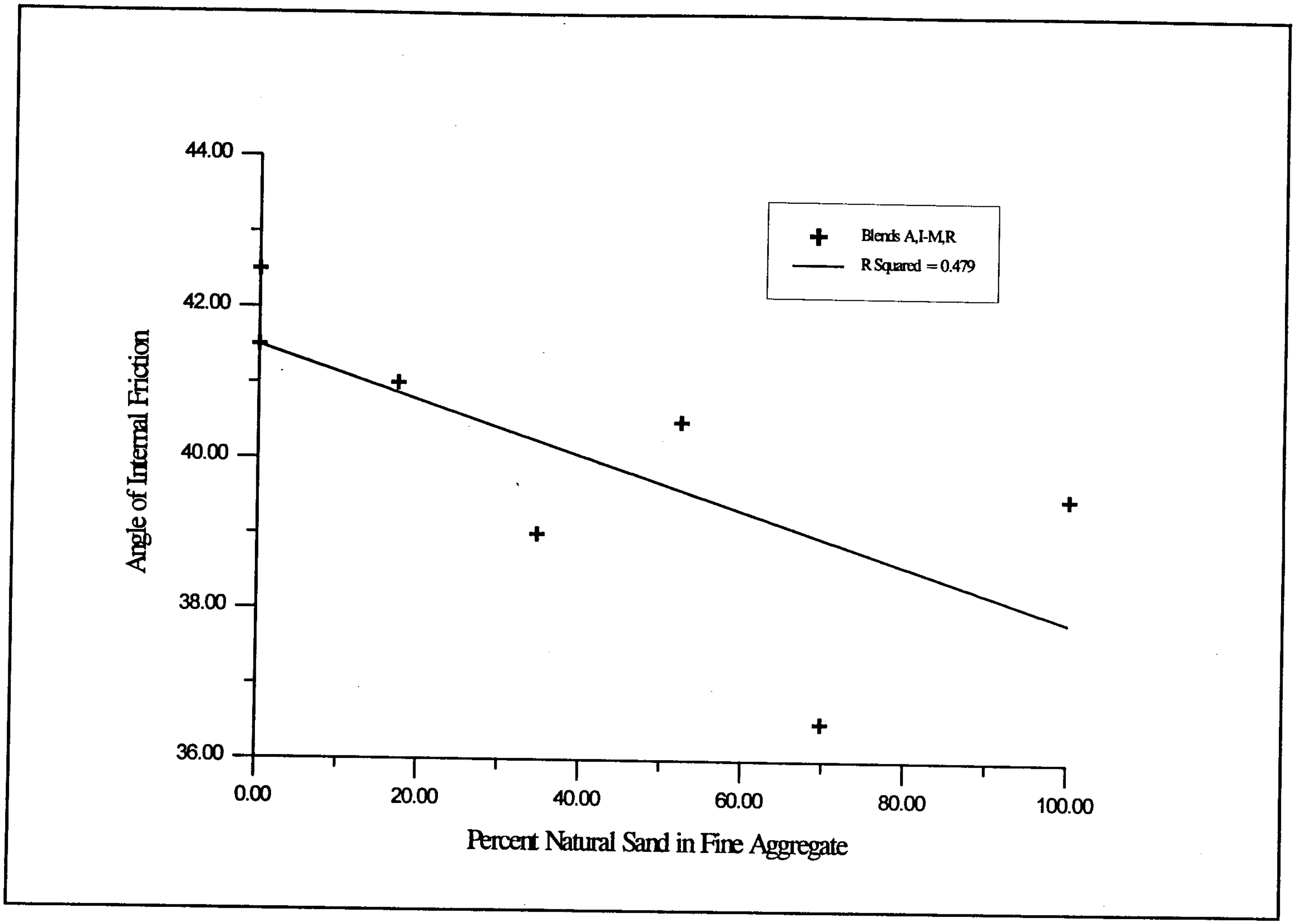


Figure 30. Angle of Internal Friction from Direct Shear Test versus Percent Natural Sand in Fine Aggregate

Correlation of Aggregate Characterization Tests with Particle Index Test

As discussed earlier in this report, the Particle Index test has proven to correlate extremely well with aggregate particle shape and surface texture. This test method is standardized, but due to the sample preparation time and time required to perform the test, this method is primarily used in research studies. Simpler, quicker test methods that correlate well with pavement performance are desirable to characterize aggregate particle shape and surface texture. Analyses were conducted to establish relationships between the Particle Index test and the Modified NAA test, ASTM C 29, NAA test, and direct shear test methods.

A summary of coefficients of determination for the aggregate particle characterization tests and the Particle Index test is presented in Table 16. The results of these correlations are shown in Figures 31-34. These correlations are separated into coarse and fine aggregate fractions. The Modified NAA test and ASTM C 29 test methods were evaluated for the coarse aggregate fraction. Each of these correlations has a strong linear correlation with the Particle Index values. The difference in these relationships is small which means any of these test methods could be used to characterize coarse aggregate shape and texture.

The Particle Index values for the fine aggregate fraction were correlated with the NAA test and direct shear test methods. The NAA test method produced a stronger correlation with Particle Index than did the direct shear test. Based on this data, the NAA particle shape and texture test could be used to characterize fine aggregate shape and texture.

Table 16. Correlation of Aggregate Particle Characterization Tests with Particle Index Values

Aggregate size	Aggregate particle characterization tests	Coefficient of determination (R^2)
Coarse	Modified NAA, As-Prepared	0.936
	ASTM C 29 (Rod), As-Prepared	0.889
	ASTM C 29 (Shovel), As-Prepared	0.928
Fine	NAA, Method A	0.808
	NAA, Method C	0.416
	Direct Shear	0.512

HMA MIXTURES

This section presents and discusses the results of the preparation and testing of the eighteen HMA mixtures produced with an AC-20 asphalt cement. These mixtures are identified in Table 1. This phase of the laboratory study was designed to determine the range of HMA mixture properties that would be expected using aggregates meeting the Item P-401 specification and the impact of deviations on the engineering properties (strength values and rutting characteristics) by using various aggregate gradations and blends with different particle shapes and textures. The aggregate gradations were selected to determine the effects of variation in the shape of an aggregate gradation curve, the percentage of crushed coarse aggregates, and the amount of natural sand material in the aggregate blend. The AC-20 asphalt cement was used in this phase because this type of asphalt binder is one of the most commonly used paving asphalt cements in the United States.

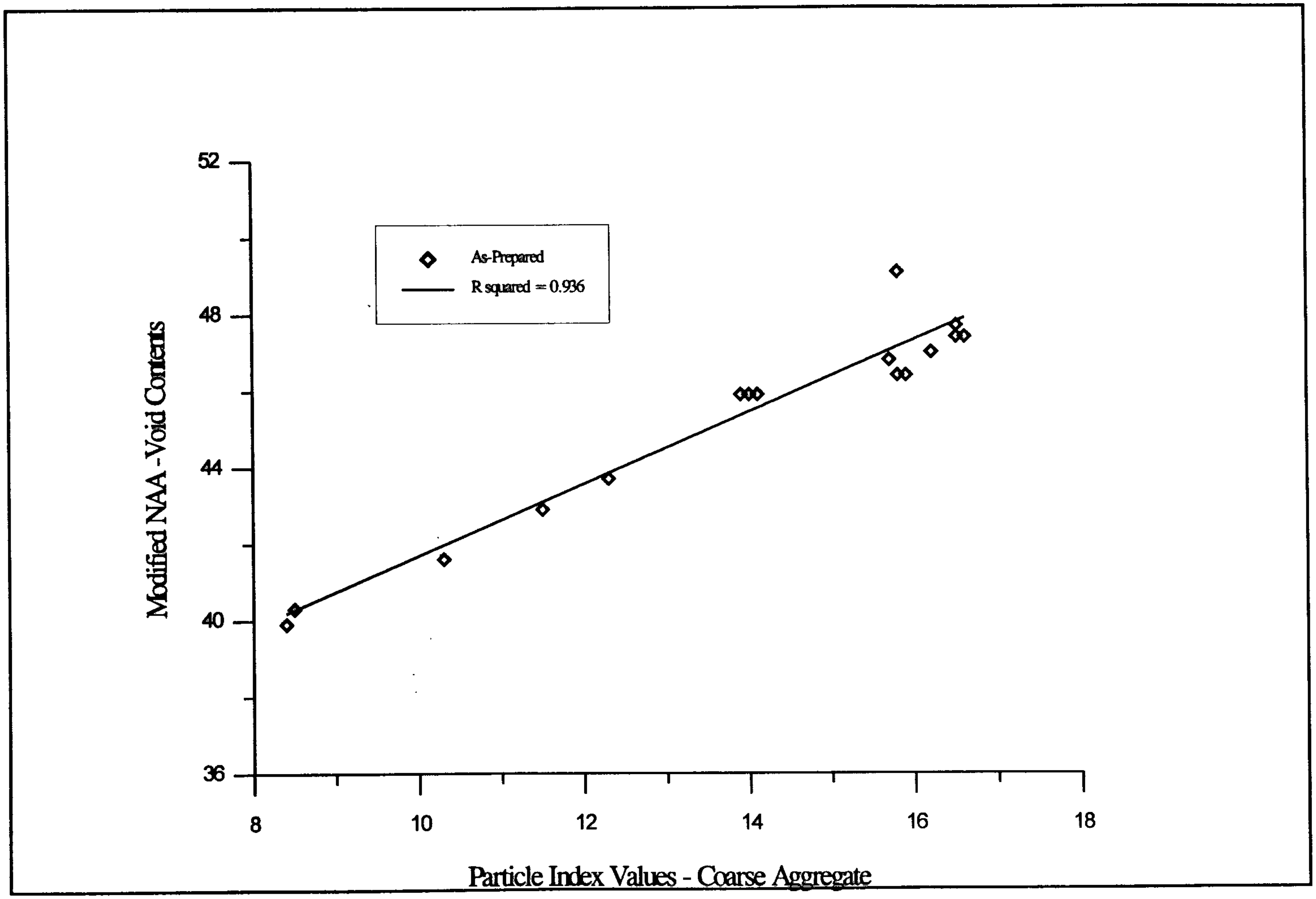


Figure 31. Modified NAA Particle Shape and Texture Void Contents versus Particle Index Values - Coarse Aggregate

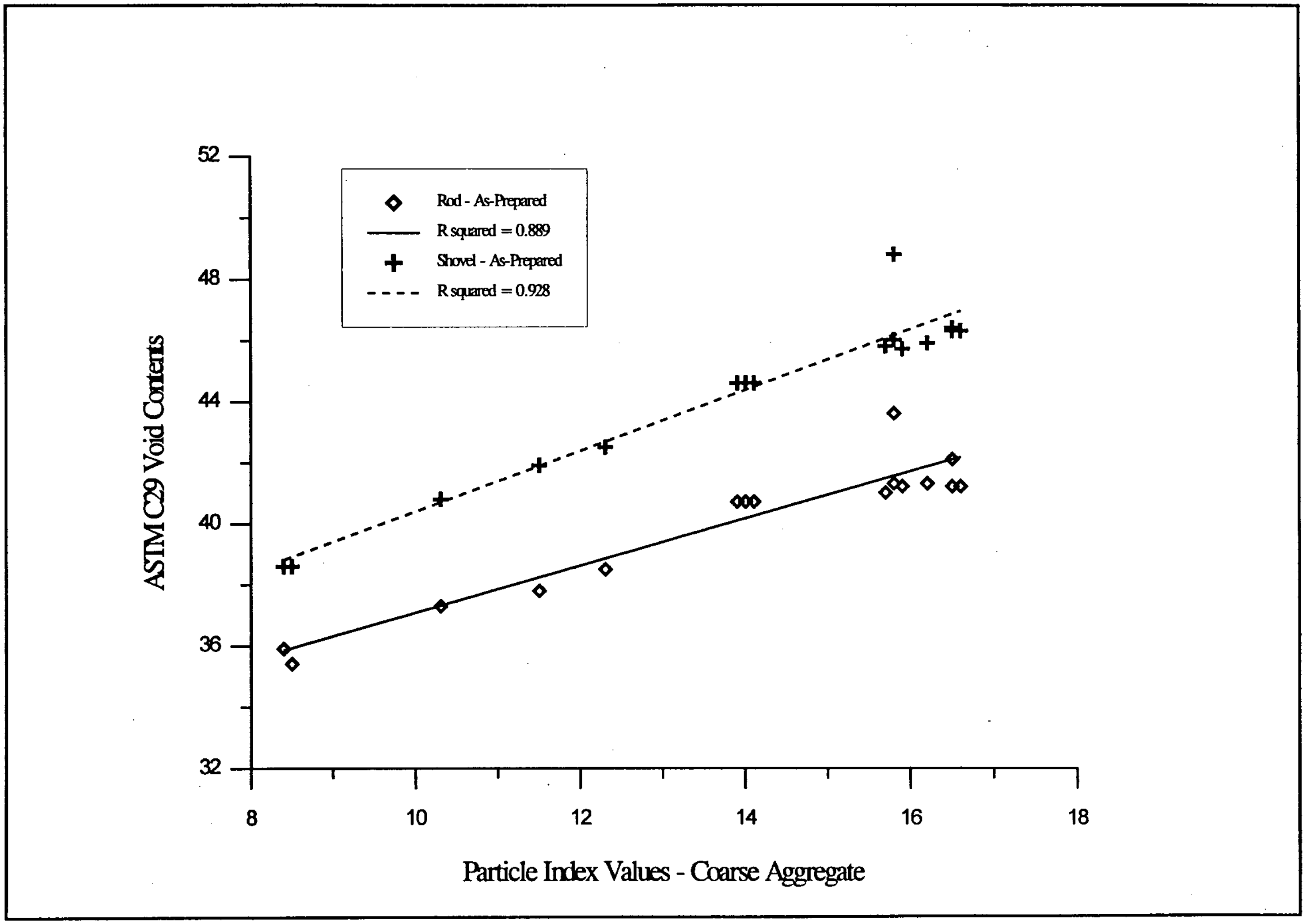


Figure 32. Void Contents from ASTM C 29 Method versus Particle Index Values - Coarse Aggregate

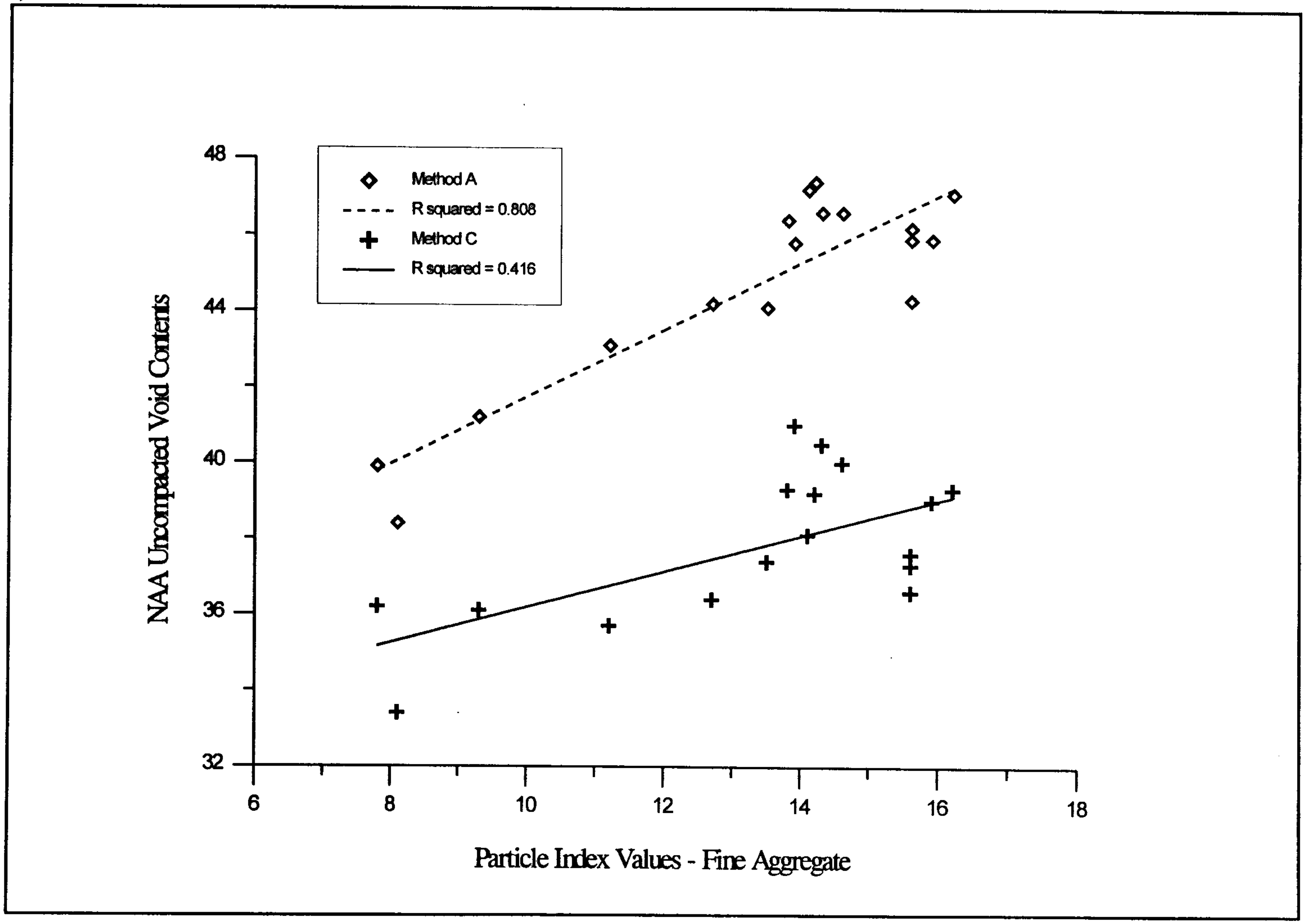


Figure 33. NAA Particle Shape and Texture Void Contents versus Particle Index Values - Fine Aggregate

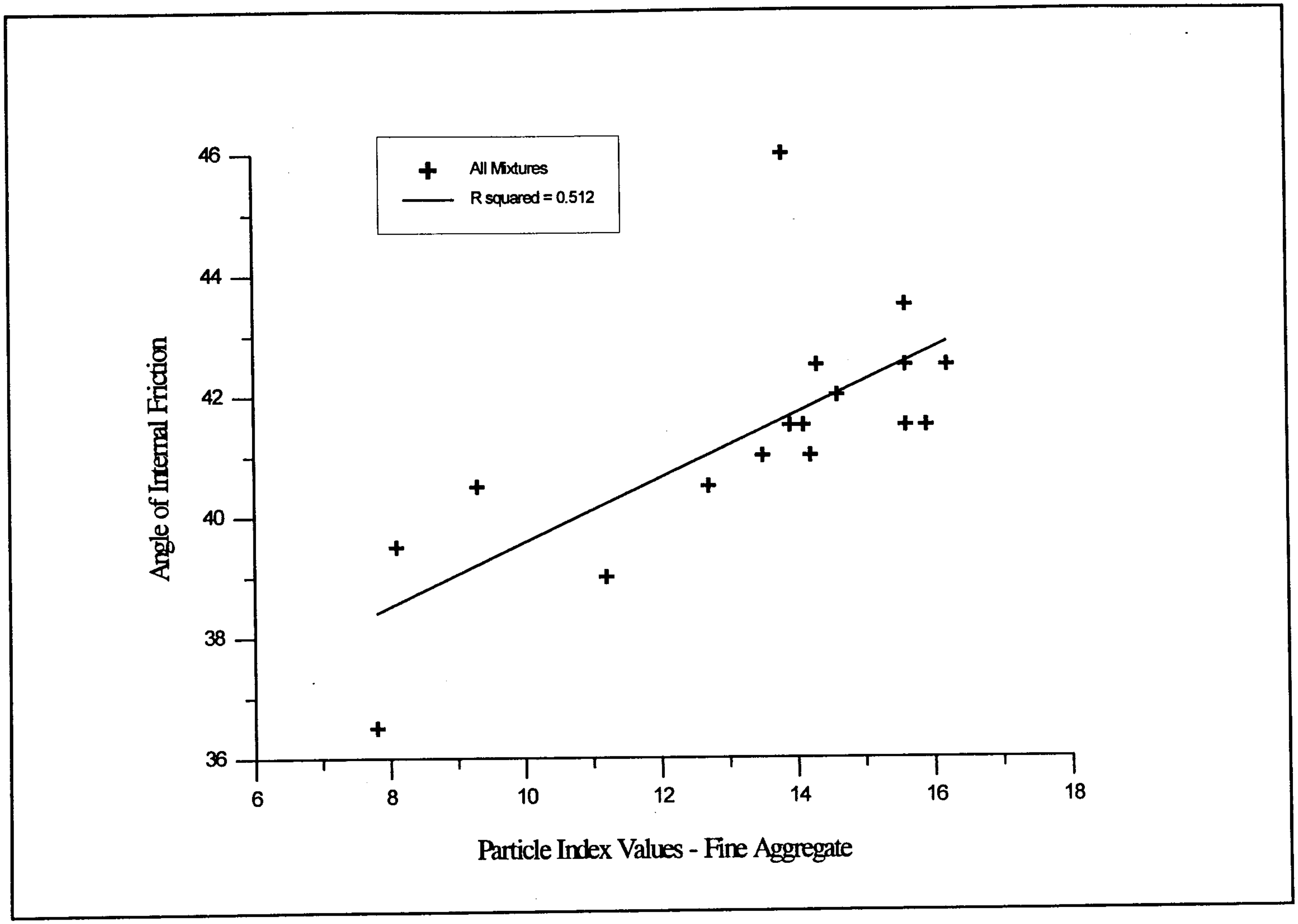


Figure 34. Angle of Internal Friction from Direct Shear Test versus Particle Index Values - Fine Aggregate

Eighteen volumetric mix designs were conducted for the aggregate blends to select an optimum asphalt content at 4 percent air voids (voids total mix). In order to insure that the asphalt content did not influence the HMA strength properties and rutting characteristics, this void criteria was selected and held constant throughout the laboratory testing. All specimens were compacted with the Gyratory Testing Machine. The asphalt mixture's strength properties and rutting characteristics were evaluated with volumetric properties, Marshall stability and flow, gyratory compaction properties, indirect tensile test, direct shear test, and the confined repeated load deformation test.

Analysis results involved determining the amount of variation of HMA mixture properties and correlating the aggregate characterization tests to the HMA mixture properties with an emphasis on pavement deformation and rutting potential.

Presentation of Test Results

Volumetric and Marshall Properties

A volumetric mix design with gyratory compaction was used to determine the optimum asphalt content for all HMA mixtures. The target for selecting the optimum asphalt content was 4 percent air voids. The design criteria specified in Item P-401 for asphalt mixtures designed for tire pressures greater than 100 psi is presented in Table 17.

Table 17. Design Criteria for HMA Mixtures - Item P-401

Test	FAA specification requirement
Compactive effort, blows	75
Stability, lbs (minimum)	2150
Flow, 0.01 in.	10 - 14
Air voids, %	2.8 - 4.2
Voids in mineral aggregate, % (minimum)	14
Voids filled, %	65 - 75

A summary of the average Marshall mix properties for the AC-20 HMA mixtures is presented in Table 18. The test results include unit weight, theoretical specific gravity, air voids, voids in mineral aggregates, voids filled with asphalt and the Marshall stability and flow values. The void parameters and gravity values are an average of 24 specimens while the stability and flow values are an average of 3 to 5 specimens.

Gyratory Compaction Properties

The Gyratory Testing Machine was used to compact all specimen for this phase of the laboratory study. The gyratory compactive effort used in this study was a 200 psi normal pressure, 1-degree gyration angle, and 30 revolutions of an oil-filled roller assembly. This compactive effort is equal to the 75-blow hand hammer effort that is normally used for heavy duty pavements. This compaction process was selected because the kneading action produces compacted specimen that have aggregate particle orientation similar to inplace pavements. The Gyratory Testing Machine also produces stress-strain measurements for each compacted specimen that can be used to evaluate the quality of an asphalt concrete

Table 18. Summary of Marshall Mix Properties at Optimum Asphalt Content for AC-20 Mixtures

Mix identification	Optimum asphalt content (%)	Bulk specific gravity	Theoretical specific gravity	Voids total mix (%)	Voids in mineral aggregate (%)	Voids filled (%)	Unit weight (pcf)	Stability (lbs)	Flow (0.01 in.)
A	4.7	2.530	2.636	4.0	15.5	74.1	157.9	2017	11.8
B	5.2	2.503	2.598	3.7	16.2	77.4	156.2	1524	12.6
C	5.0	2.500	2.601	3.9	15.9	75.6	156.0	2232	12.3
D	5.6	2.481	2.582	3.9	17.3	77.4	154.8	2145	11.3
E	4.3	2.523	2.633	4.2	14.6	71.4	157.4	2014	12.9
F	4.9	2.510	2.608	3.8	15.6	76.0	156.6	2125	11.3
G	4.6	2.500	2.614	4.4	15.5	71.7	156.0	1872	10.7
H	4.0	2.530	2.636	4.0	13.8	70.9	157.9	1851	10.8
I	7.0	2.277	2.368	3.8	19.2	80.0	142.1	2035	13.0
J	6.5	2.295	2.387	3.8	18.2	78.9	143.2	1554	11.1
K	6.0	2.314	2.406	3.8	17.2	77.8	144.4	1610	10.2
L	5.8	2.320	2.415	3.9	16.9	76.7	144.8	1370	9.4
M	5.6	2.328	2.426	4.1	16.6	75.6	145.2	1107	8.0
N	6.7	2.277	2.376	4.2	18.8	78.0	142.1	1610	11.8
O	6.7	2.285	2.375	3.8	18.5	79.8	142.6	1523	11.4
P	6.3	2.294	2.387	4.0	17.9	77.7	143.0	1525	11.3
Q	6.2	2.291	2.389	4.1	17.8	76.8	142.9	1454	10.4
R	4.7	2.348	2.437	3.7	14.3	74.1	146.5	1192	8.9

mixture. A summary of the average gyratory compaction properties for the AC-20 HMA mixtures is presented in Table 19. These test results include the GSI, GEPI, and gyratory shear strength values.

Table 19. Summary of Gyratory Compaction Properties for AC-20 HMA Mixtures

Mix identification	Thickness (in.)	Gyratory stability index (GSI)	Gyratory elasto-plastic index (GEPI)	Gyratory shear strength (psi)
A	2.458	1.01	1.24	104
B	2.509	0.99	1.28	115
C	2.470	0.99	1.24	130
D	2.477	0.99	1.29	111
E	2.451	1.00	1.24	124
F	2.460	0.99	1.22	110
G	2.453	1.00	1.19	120
H	2.469	0.99	1.24	172
I	2.705	1.00	1.46	159
J	2.677	0.99	1.45	200
K	2.653	0.99	1.50	179
L	2.624	0.99	1.54	203
M	2.602	0.99	1.56	213
N	2.690	0.99	1.50	191
O	2.690	0.99	1.52	197
P	2.677	0.99	1.55	206
Q	2.613	1.00	1.55	149
R	2.542	0.99	1.67	164

Indirect Tensile

The indirect tensile test was conducted to determine the tensile strength of the various HMA mixtures. This test was conducted on a minimum of three specimen at test temperatures of 77°F and 104°F. These test temperatures were selected to evaluate the various aggregate properties at medium and high pavement temperatures where most pavement rutting occurs. The tensile strengths calculated according to ASTM D 4123 are summarized in Table 20 for the AC-20 HMA mixtures.

Direct Shear

The direct shear test was conducted to determine the shear strength of HMA mixtures under several normal stress conditions. A standard Marshall specimen (4-in.-diameter and 2-in.-thick) was sheared at 140°F in the simple shear test device. The shear load was applied at a constant rate until failure. At failure, the maximum shear load and displacement were recorded. The shear strength values were determined for three normal stress levels (100, 200, 300 psi). The calculated shear strength values and the analytically determined angle of internal friction and cohesion values are presented in Table 21. Six specimen were tested for each mixture.

Table 20. Summary of Indirect Tensile Values for AC-20 Mixtures

Mix identification	Tensile strength at 77°F (psi)	Tensile strength at 104°F (psi)
A	97.5	35.8
B	68.8	31.0
C	99.6	42.7
D	93.0	45.9
E	102.2	45.4
F	93.7	48.7
G	100.6	44.0
H	99.3	45.6
I	70.9	29.5
J	56.7	30.2
K	61.9	31.2
L	75.4	32.3
M	67.6	25.7
N	91.3	22.5
O	83.2	28.4
P	102.5	31.2
Q	78.0	24.3
R	84.4	38.7

Table 21. Summary of Direct Shear Data for AC-20 Mixtures

Mix identification	Angle of internal friction (ϕ)	Cohesion-Y-axis intercept (psi)	Shear strengths at normal stress levels		
			100 psi (psi)	200 psi (psi)	300 psi (psi)
A	21.6	42.8	78.0	130.8	157.1
B	19.3	46.5	84.5	110.3	154.4
C	22.8	33.2	76.2	115.5	160.5
D	17.9	53.9	84.8	121.1	149.3
E	19.2	62.7	94.5	138.1	164.0
F	18.2	67.9	94.3	146.5	160.1
G	18.1	59.6	86.6	136.5	151.9
H	14.5	71.9	97.1	125.3	148.9
I	15.6	46.9	73.5	105.2	129.2
J	11.5	52.7	72.8	94.2	113.6
K	14.7	45.7	70.9	100.1	123.3
L	16.0	39.6	69.3	95.2	126.8
M	16.2	32.4	63.8	86.0	122.1
N	13.7	40.8	67.0	86.0	115.9
O	7.7	74.7	91.4	95.5	118.5
P	13.9	43.7	66.4	97.6	116.0
Q	13.7	53.3	68.6	120.3	117.5
R	15.0	28.3	55.6	80.6	109.1

Confined Repeated Load Deformation

The confined repeated load deformation test was conducted to evaluate and determine the rutting characteristics of the AC-20 HMA mixtures. The confined repeated load deformation test is considered to be one of the best laboratory test procedures to evaluate asphalt concrete mixtures for rutting potential. The test temperature of 140°F was used to simulate maximum pavement temperatures and to enhance the influence of aggregate properties on the mixture's behavior. A summary of the confined repeated load deformation tests is presented in Table 22. These test results include deformation or strain values, creep modulus or stiffness values, and the slope of the creep curve plotted on a log-log scale. The confined repeated load deformation test was conducted on a minimum of 3 specimen for each mixture. Details of the test results are presented in Table B1.

Analysis and Discussion of Test Results

This phase of the laboratory study was conducted to evaluate the engineering properties (strength values and rutting characteristics) of each HMA mixture produced with an AC-20 asphalt binder. This laboratory testing determined the range of properties that would be expected using aggregates meeting the P-401 specification and the impact of deviations on engineering properties by using various aggregate gradations and particle shapes. The analysis of the test results involved determining the amount of variation of HMA mixture properties when different gradations and particle shapes were used and correlating the aggregate particle characterization tests to the permanent deformation properties. An additional analysis was conducted to correlate the relationship of HMA mixture properties with the rutting characteristic test results of the confined repeated load deformation test.

Table 22. Summary of Confined Repeated Load Deformation Test Data for AC-20 Mixtures

Mix identification	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
A	2.446	4.0	0.0211	0.0211	9479	0.109
B	2.546	3.8	0.0284	0.0283	7042	0.212
C	2.479	3.9	0.0206	0.0205	9709	0.093
D	2.478	3.9	0.0205	00200	9756	0.085
E	2.468	4.3	0.0270	0.0266	7407	0.171
F	2.475	3.7	0.0148	0.0146	13514	0.121
G	2.473	4.4	0.0151	0.0145	13245	0.105
H	2.478	4.1	0.0232	0.0230	8620	0.115
I	2.737	4.3	0.0352	0.0352	5682	0.243
J	2.677	4.1	0.0355	0.0350	5633	0.214
K	2.638	4.0	0.0387	0.0386	5168	0.253
L	2.606	3.7	0.0394	0.0384	5076	0.195
M	2.614	4.1	0.0400	0.0399	5000	0.259
N	2.704	4.2	0.0408	0.0407	4902	0.213
O	2.651	3.9	0.0453	0.0452	4415	0.238
P	2.674	3.9	0.0447	0.0445	4474	0.248
Q	2.639	4.1	0.0495	0.0495	4040	0.247
R	2.507	3.7	0.0849	0.0843	2356	0.365

The test aggregate gradations were selected and designed to determine the effects of variation in the shape of an aggregate gradation curve (Mixes A-H), the percentage of crushed coarse aggregate (Mixes I, N-R), and the amount of natural sand material in the aggregate blend (Mixes A, I-M, R). In order to determine percent difference, an accepted standard or control mixture (middle of FAA gradation band) was established. Mix A (crushed limestone) and Mix I (crushed gravel) were selected as the control mixtures for their respective aggregate types. Mix A was the control mixture for the evaluation of the shape of the aggregate gradation curve and Mix I was the control mixture for the evaluation of the percentage of crushed coarse aggregate and the amount of natural sand in the aggregate blend.

Variation in Shape of Aggregate Gradation Curve

The effect of variation in the shape of an aggregate gradation curve was evaluated in Mixes A-H. These aggregate blends were produced with crushed limestone and various amounts of natural sand (less than maximum limit of 15 percent). These target gradations were fabricated to evaluate the shape of gradation curve with minimal particle shape effects.

Several observations and trends were observed from the confined repeated load deformation test results. The effect of the shape of the aggregate gradation curve was evident in the permanent strain values, creep modulus values, and the slope of the log-log creep curve. The mixtures that produced the better rutting characteristics were two gradations finer than the maximum density line (Mixes C and D) and two poorly-graded gradations (Mixes F and G). Each of these mixtures produced better rutting characteristics than the mixture produced with an aggregate gradation falling on the center of the FAA gradation band (Mix A). The two poorly-graded gradations have large percentages of material retained on the No. 4 sieve which can produce stone on stone contact (similar to SMA mixtures).

The differences in the confined repeated load deformation test results are presented in Table 23 and shown graphically in Figures 35-37. The permanent strain value for the control mixture was 0.0211 in/in. Mixes C, D, F, and G produced strain values lower than the control mixture by 2.8 to 31.3 percent. Mixes F and G produced almost a third less permanent deformation. Mixes B and E produced permanent deformation values 26.1 and 34.1 percent greater than the control mixture. The trends for the creep modulus values followed the trends for the permanent strain values. The slope values indicated that Mixes C, D and G produced the lowest rate of rutting while Mixes B and E produced the highest rate of rutting. The percent difference (increase) in rate of rutting for Mixes B and E was significantly large, 94.5 and 56.9 percent, respectively.

Percentage of Crushed Coarse Aggregate

The effect of the percentage of crushed gravel coarse aggregates was evaluated in Mixes I, N-Q. The confined repeated load deformation test results indicated that the percentage of crushed coarse aggregate did affect the rutting characteristics of these mixtures. The overall trend was as the percentage of crushed coarse aggregate decreased, the rutting potential for the mixtures increased. The slope of the creep curve indicated no trend as the percentage of crushed coarse aggregate varied. The calculated percent difference for these test results are presented in Table 24 and shown graphically in Figures 38 and 39. Based on the test results, the potential for rutting increases significantly when the percentage of crushed coarse aggregate is 70 percent or less. By decreasing the percentage of crushed coarse aggregate from 100 percent to 70 percent, the permanent strain value increases 15.6 percent.

Table 23. Confined Repeated Load Deformation Test Results for AC-20 Mixtures Evaluating the Shape of the Aggregate Gradation Curve

Mix identification	Permanent strain (in/in.)	Percent difference (1)	Creep modulus (psi)	Percent difference (2)	Slope of creep curve (M)	Percent difference (3)
A	0.0211	--	9479	--	0.109	--
B	0.0283	+ 34.1	7042	- 25.7	0.212	+ 94.5
C	0.0205	- 2.8	9709	+ 2.4	0.093	- 14.7
D	0.0200	- 5.2	9756	+ 2.9	0.085	- 22.0
E	0.0266	+ 26.1	7407	- 21.9	0.171	+ 56.9
F	0.0146	- 30.8	13514	+ 42.6	0.121	+ 11.0
G	0.0145	- 31.3	13245	+ 39.7	0.105	- 3.7
H	0.0230	+ 9.0	8620	- 9.1	0.115	+ 5.5

Mix A - Center of gradation band
Mix B - Coarse side of band
Mix C - Fine side of band
Mix D - Finer than upper limit
Mix E - Excessive No. 200
Mix F - Poorly graded - middle
Mix G - Poorly graded - coarse
Mix H - Poorly graded - fine

(1) Positive (+) difference - increased rutting potential.
(2) Positive (+) difference - decreased rutting potential.
(3) Positive (+) difference - increased rutting potential.

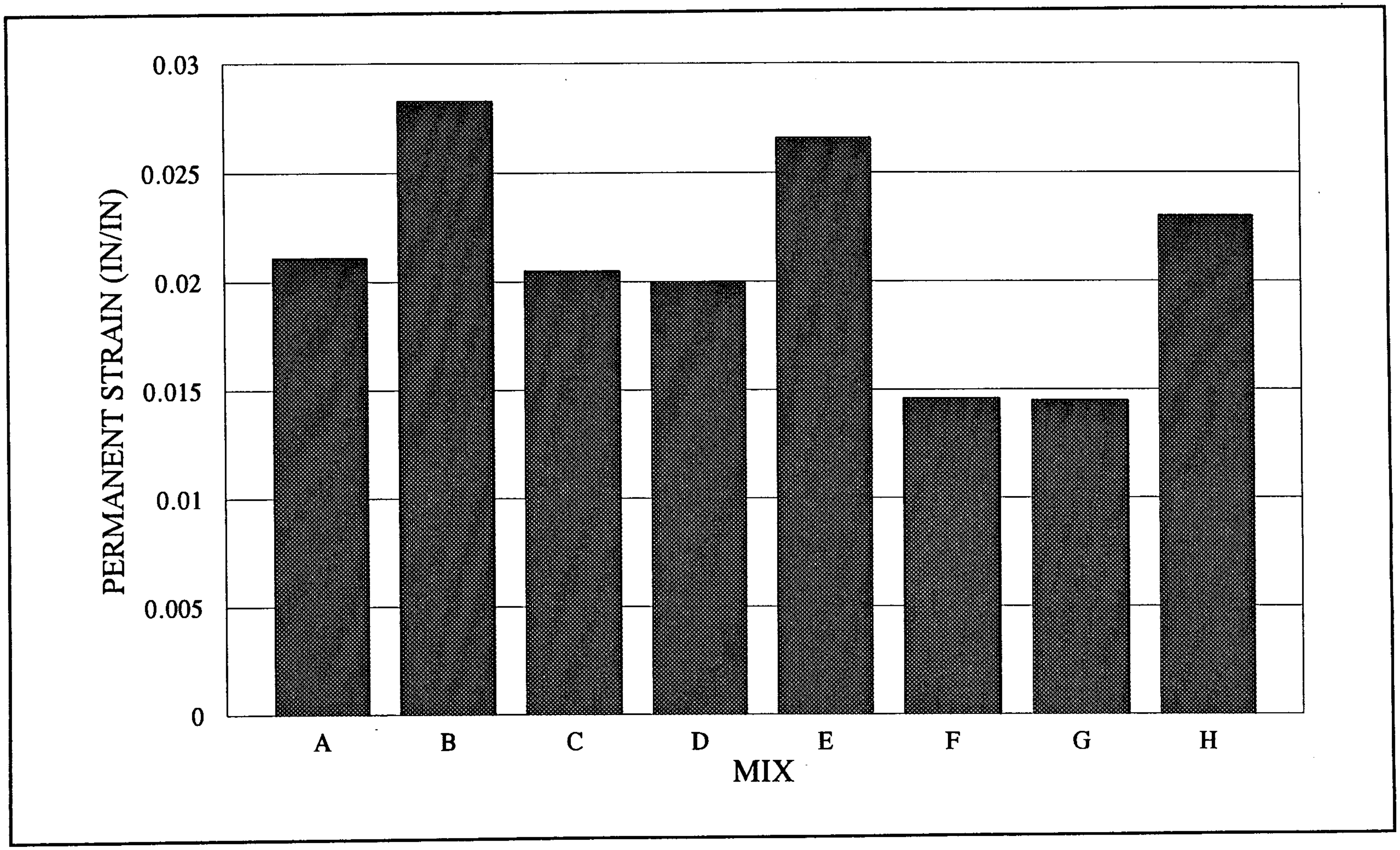


Figure 35. Effect of Shape of Aggregate Gradation on Permanent Strain Values for AC-20 Mixtures

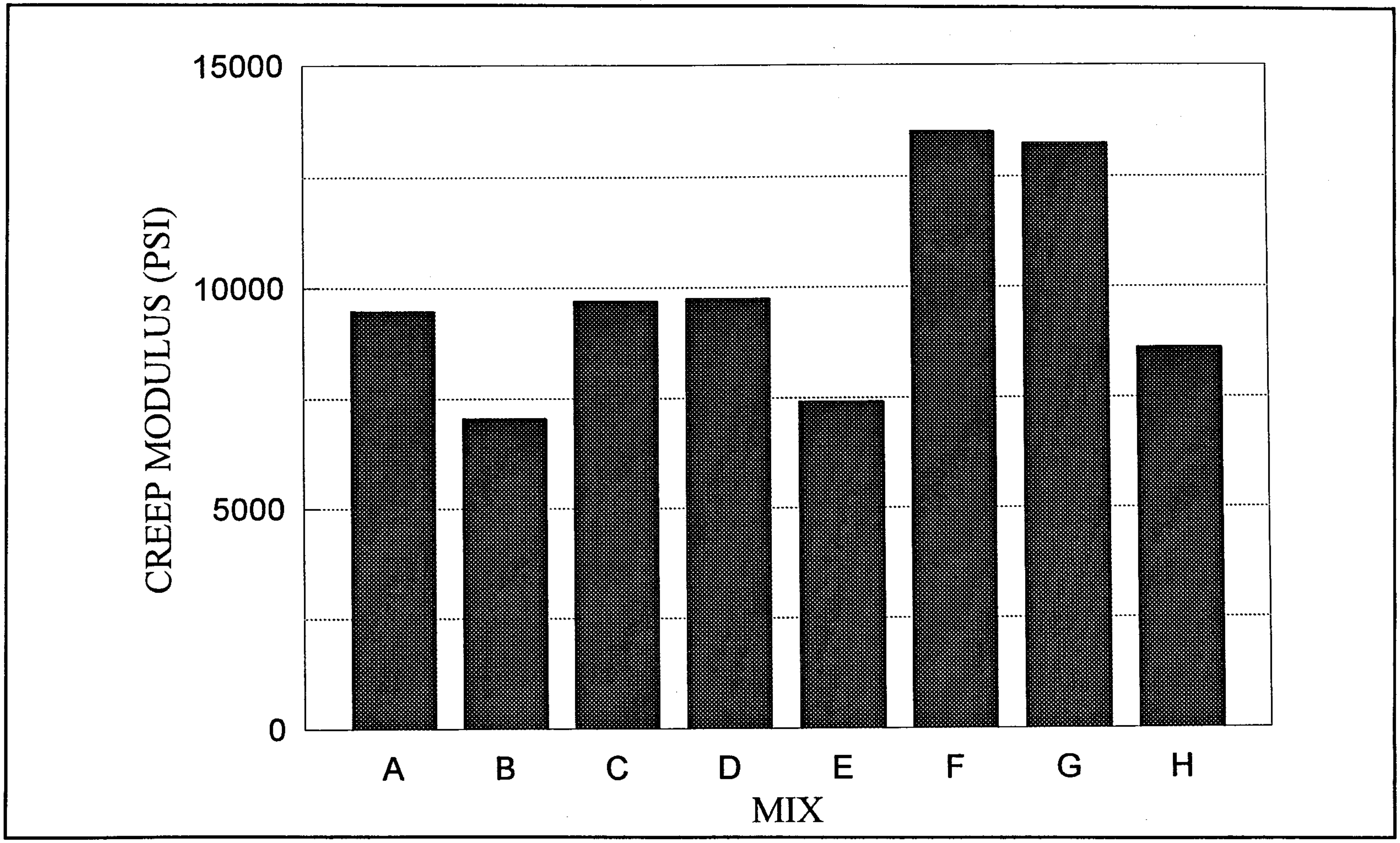


Figure 36. Effect of Shape of Aggregate Gradation on Creep Modulus Values for AC-20 Mixtures

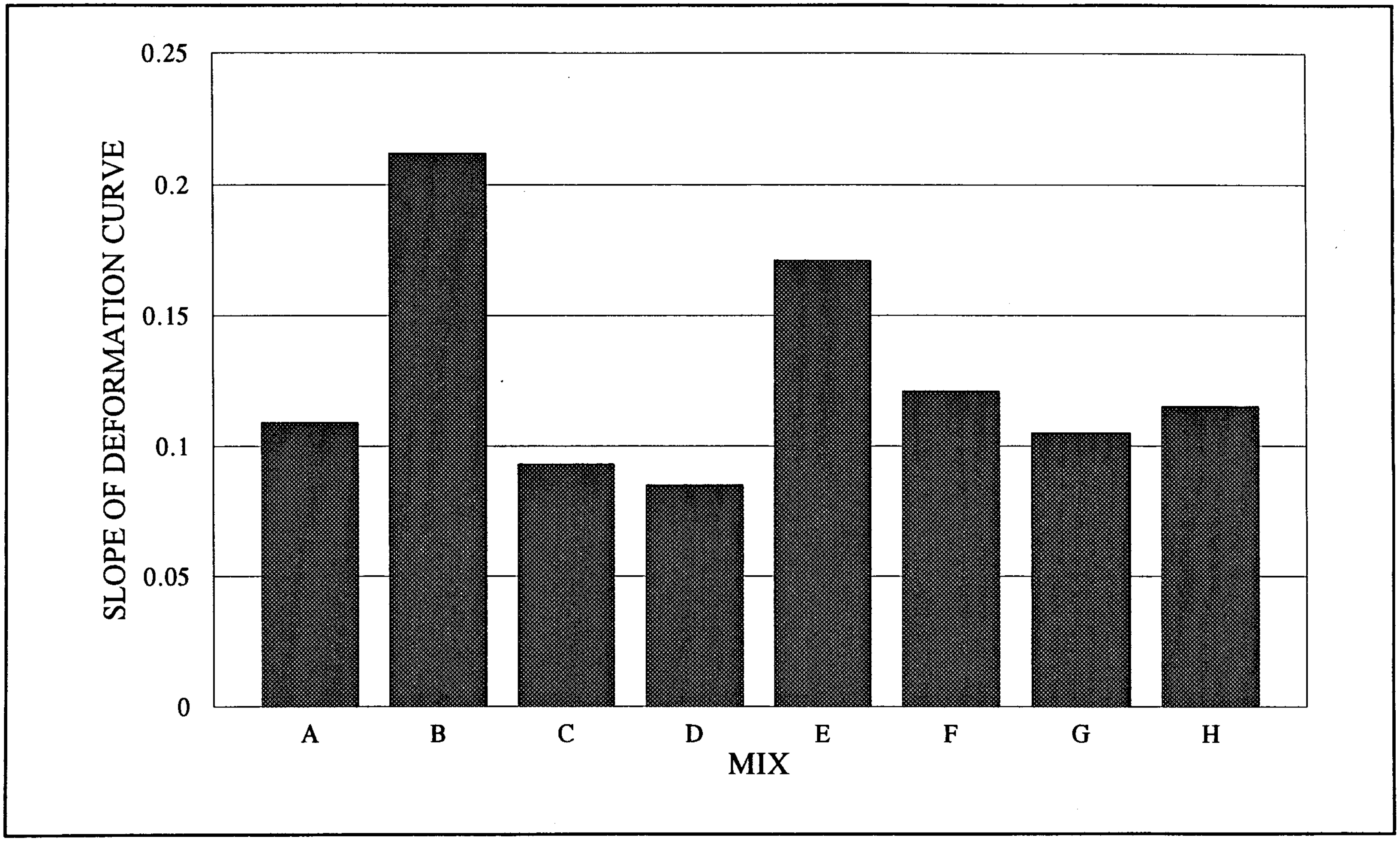


Figure 37. Effect of Shape of Aggregate Gradation on Slope of Deformation Curve for AC-20 Mixtures

Table 24. Confined Repeated Load Deformation Test Results for AC-20 Mixtures Evaluating the Percentage of Crushed Coarse Aggregate

Mix identification	Percent crushed coarse aggregate	Permanent strain (in/in.)	Percent difference (1)	Creep modulus (psi)	Percent difference (2)	Slope of creep curve (M)	Percent difference (3)
I	100	0.0352	--	5682	--	0.243	--
N	70	0.0407	+ 15.6	4902	- 13.7	0.213	- 12.4
O	50	0.0452	+ 28.4	4415	- 22.3	0.238	- 2.1
P	30	0.0445	+ 26.4	4474	- 21.3	0.248	+ 2.1
Q	0	0.0495	+ 40.6	4040	- 28.9	0.247	+ 1.7

(1) Positive (+) difference - increased rutting potential.
(2) Positive (+) difference - decreased rutting potential.
(3) Positive (+) difference - increased rutting potential.

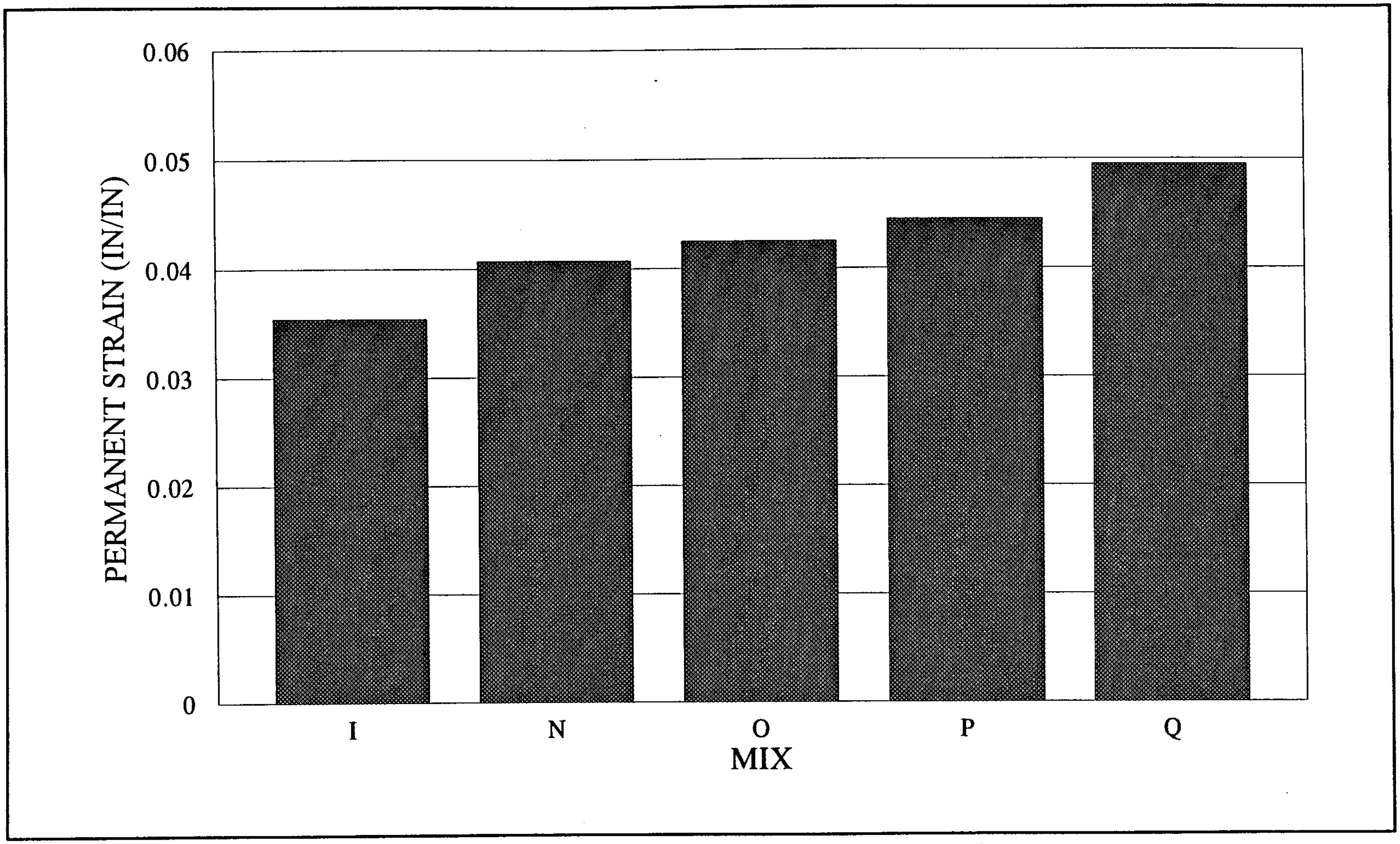


Figure 38. Effect of Percentage of Crushed Coarse Aggregate on Permanent Strain Values for AC-20 Mixtures

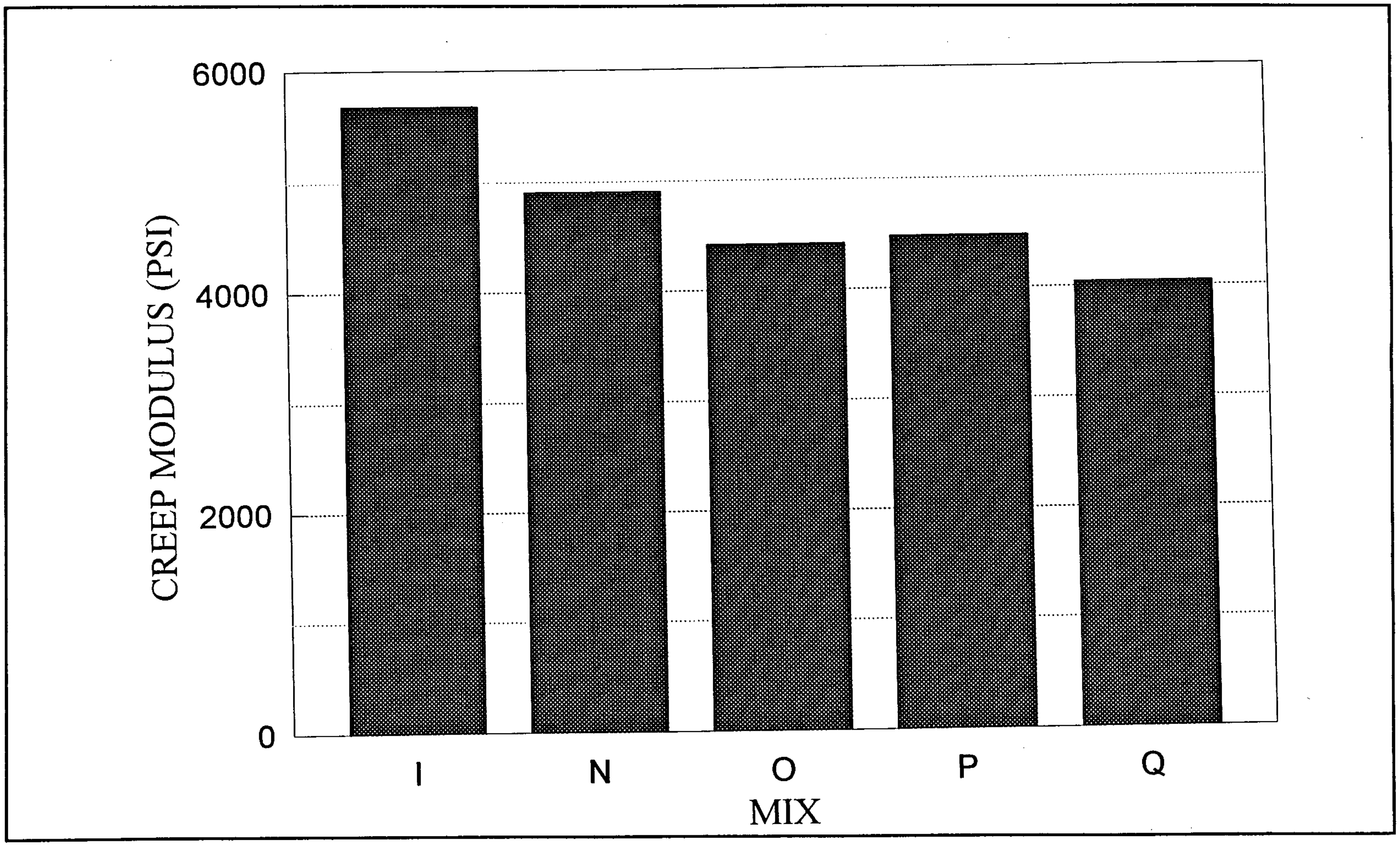


Figure 39. Effect of Percentage of Crushed Coarse Aggregate on Creep Modulus Values for AC-20 Mixtures

Amount of Natural Sand Material

The effect of the amount of natural sand material in the fine aggregate was evaluated in Mixes I-M. This evaluation combines the effect of particle shape and fine aggregate gradation. The confined repeated load deformation test results indicated that the amount of natural sand in the asphalt mixture did affect the rutting characteristics. The primary trend for the permanent strain value was to increase as the amount of natural sand increased while creep modulus decreased in value with an increase in the amount of natural sand. The slope of the log-log creep curve indicated no trend as the amount of natural sand was varied. The calculated percent difference for these test results are presented in Table 25 and shown graphically in Figures 40 and 41. Based on the test results, the potential for rutting increases when the percent of natural sand is 20 percent or greater of the total aggregate blend.

Table 25. Confined Repeated Load Deformation Test Results for AC-20 Mixtures Evaluating the Amount of Natural Sand Material

Mix identification	Percent natural sand	Permanent strain (in/in.)	Percent difference (1)	Creep modulus (psi)	Percent difference (2)	Slope of creep curve (M)	Percent difference (3)
I	0	0.0352	--	5682	--	0.243	--
J	10	0.0350	- 0.6	5633	- 0.9	0.214	- 11.9
K	20	0.0386	+ 9.7	5168	- 9.1	0.253	+ 4.1
L	30	0.0384	+ 9.1	5076	- 11.7	0.195	- 19.8
M	40	0.0399	+ 13.4	5000	- 12.0	0.259	+ 6.5

(1) Positive (+) difference - increased rutting potential.
(2) Positive (+) difference - decreased rutting potential.
(3) Positive (+) difference - increased rutting potential.

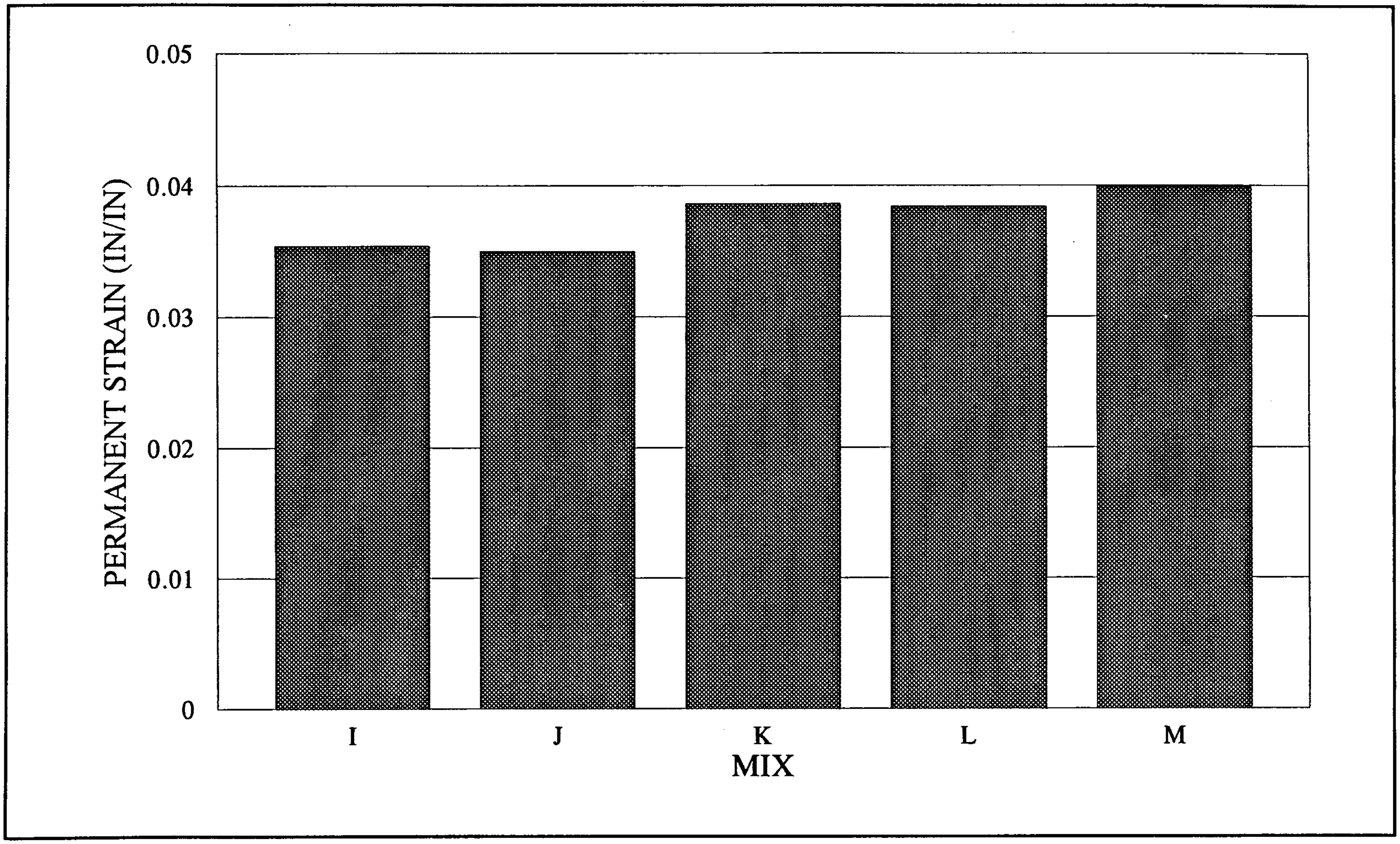


Figure 40. Effect of Natural Sand Content on Permanent Strain Values for AC-20 Mixtures

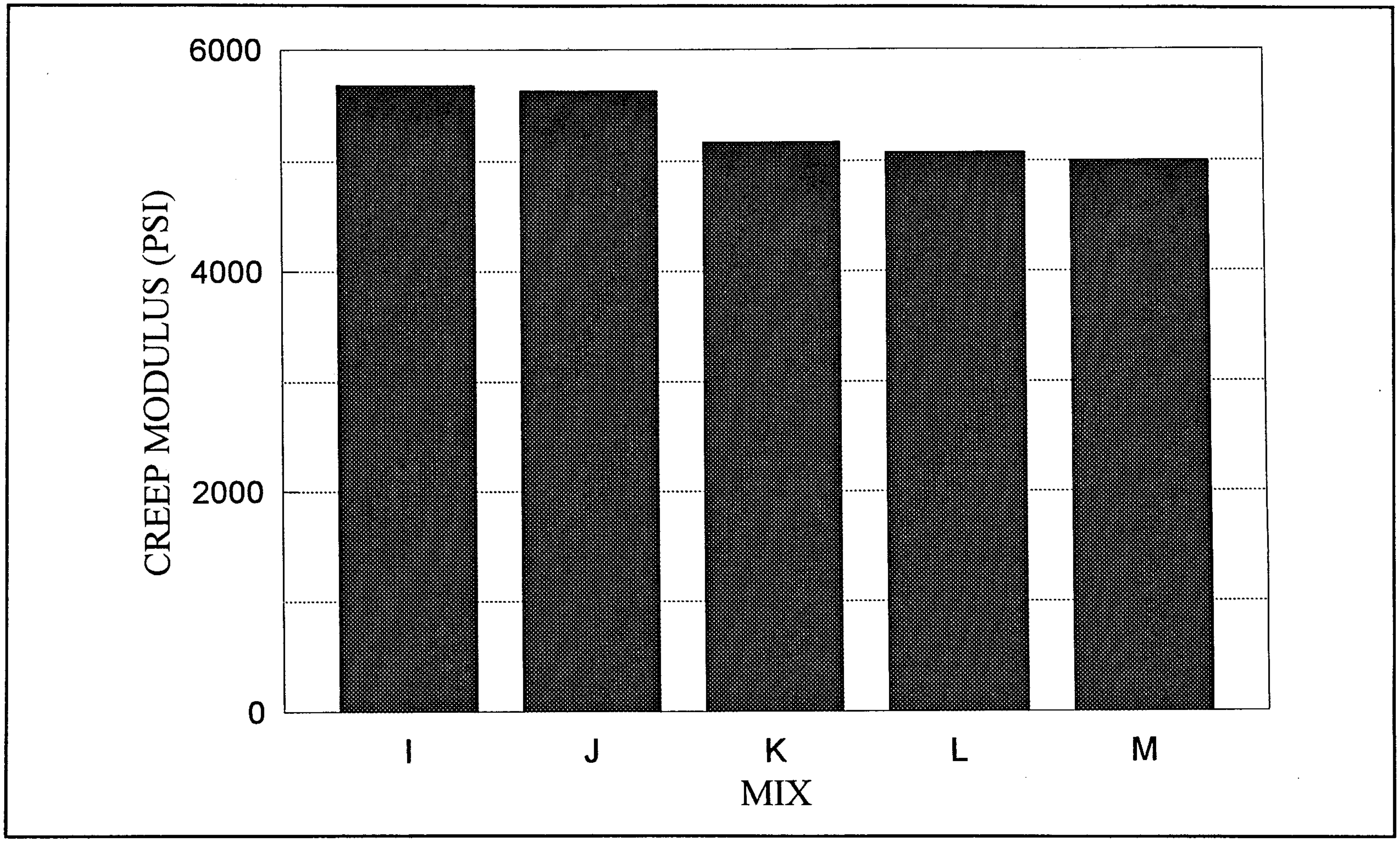


Figure 41. Effect of Natural Sand Content on Creep Modulus Values for AC-20 Mixtures

Correlation of Aggregate Characterization Tests with Permanent Deformation Properties

Based on the findings for the aggregate characterization tests, five methods were selected to be correlated with the permanent deformation properties. The characterization for the aggregate particles was divided into three aggregate fractions; composite, coarse, and fine. The composite aggregate fraction was characterized with percent crushed particles, and Particle Index values. The coarse aggregate fraction was characterized with percent crushed coarse particles, Particle Index, and Modified NAA particle shape and texture values. The fine aggregate fraction was characterized with percent crushed fine particles, natural sand content, Particle Index, and NAA particle shape and texture values. The permanent deformation properties selected for evaluation were permanent strain, creep modulus, and slope of the creep curve.

A summary of the coefficients of determination for the aggregate particle characterization tests and the permanent deformation properties is presented in Table 26. The results of the stronger correlations are shown in Figures 42-44. The correlations for permanent strain values indicated that the composite blend aggregate characterization tests had the highest correlations. The R^2 values for the Particle Index and percent crushed particles were 0.820 and 0.784 respectively. The highest correlations for creep modulus values with the aggregate characterization tests were with the Particle Index values for coarse aggregate ($R^2 = 0.570$) and the modified NAA uncompacted void contents ($R^2 = 0.567$). The correlations for the slope of deformation curve were best explained with the composite Particle Index values ($R^2 = 0.695$).

Table 26. Rankings for Correlations of Aggregate Characterization Tests with Permanent Deformation Properties for AC-20 Mixtures

Rank	Permanent strain	Creep modulus	Slope of deformation curve
1	PI[1] - Composite (0.820)	PI - Coarse (0.570)	PI - Composite (0.695)
2	PCP[2] - Composite (0.784)	Modified NAA (0.567)	PI - Coarse (0.654)
3	PI - Coarse (0.783)	PI - Composite (0.542)	Modified NAA (0.625)
4	Modified NAA (0.775)	PCP - Composite (0.378)	PCP - Composite (0.527)
5	PCP - Coarse (0.630)	PCP - Coarse (0.349)	NAA - Method A (0.451)
6	NAA - Method A (0.484)	NAA - Method A (0.314)	PCP - Coarse (0.404)
7	NSC[3] (0.269)	PI - Fine (0.085)	NSC (0.188)
8	PCP - Fine (0.191)	NSC (0.074)	PI - Fine (0.172)
9	PI - Fine (0.183)	PCP - Fine (0.064)	PCP - Fine (0.158)

[1] PI - Particle Index.
[2] PCP - Percent crushed particle.
[3] NSC - Natural sand content.

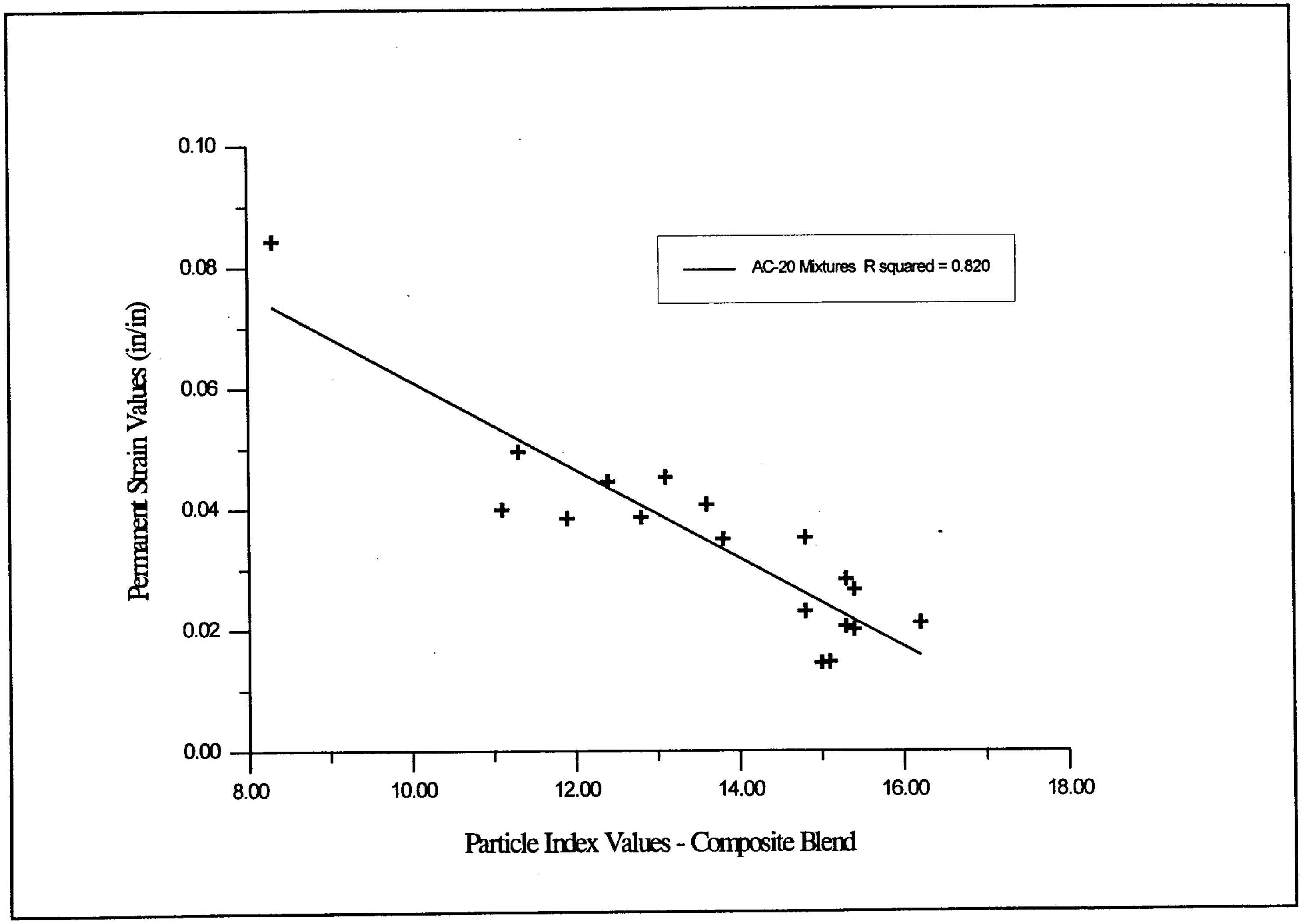


Figure 42. Permanent Strain Values for AC-20 Mixtures versus Particle Index Values - Composite Blend

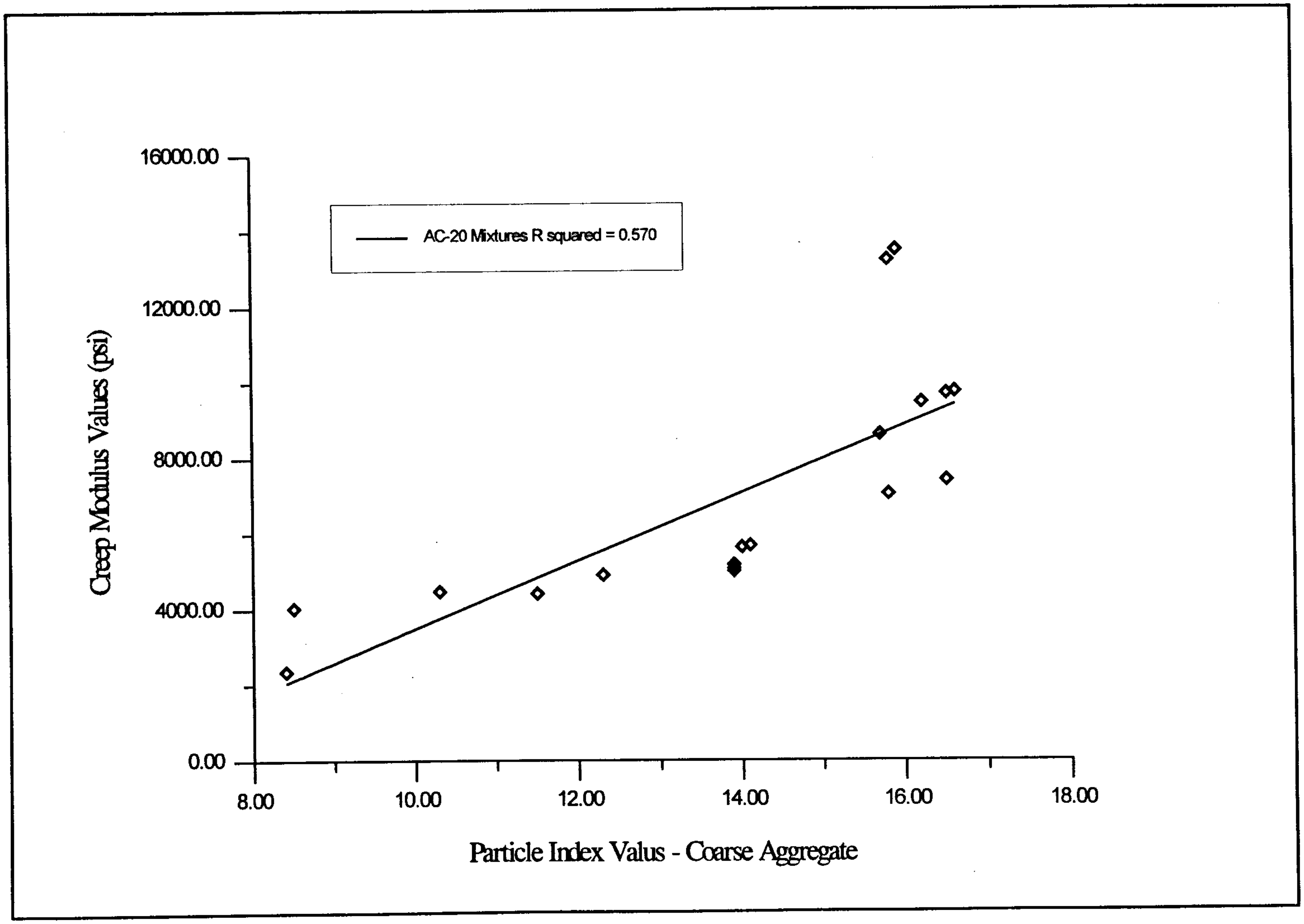


Figure 43. Creep Modulus Values for AC-20 Mixtures versus Particle Index Values - Coarse Aggregate

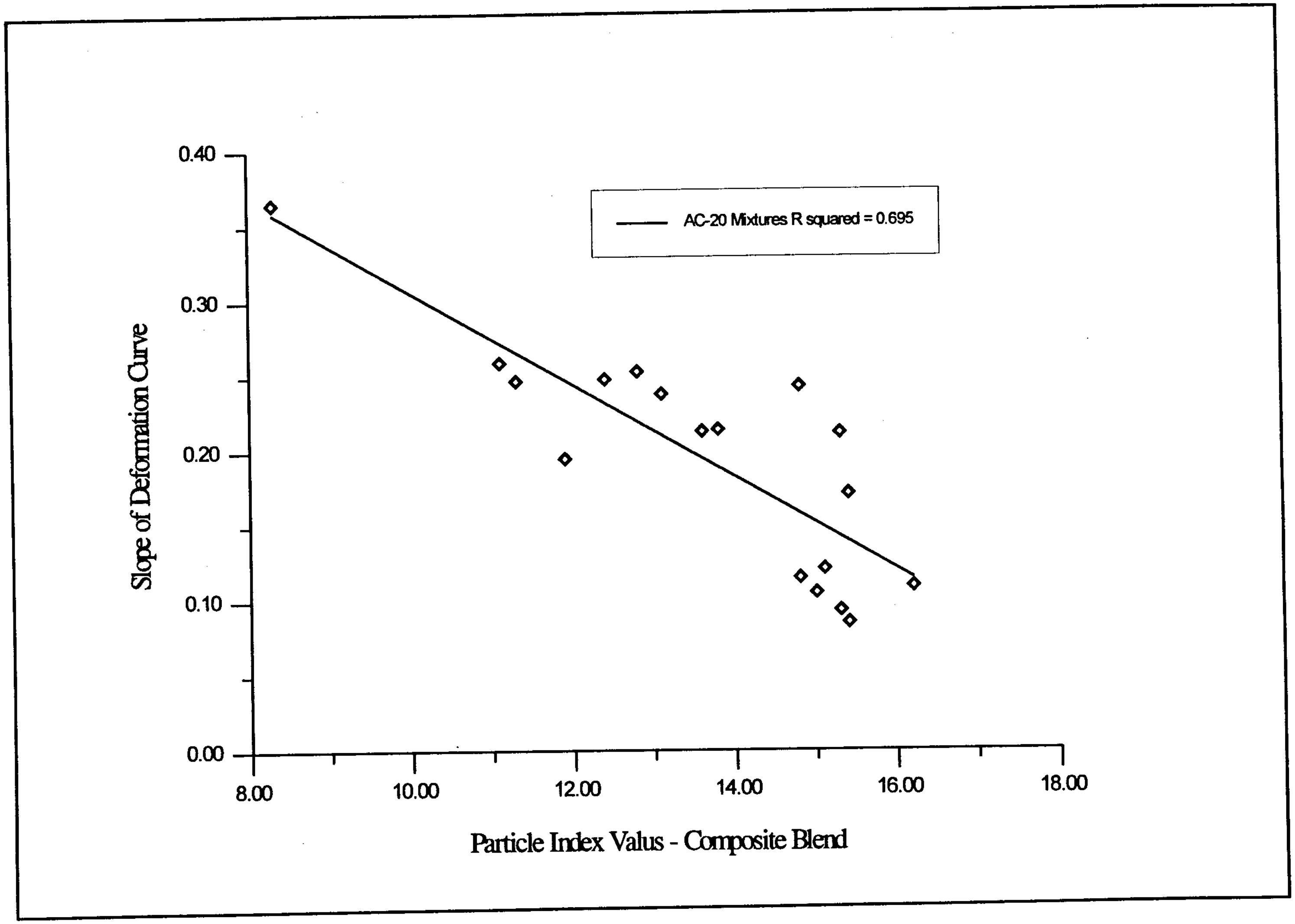


Figure 44. Slope of Deformation Curve Values for AC-20 Mixtures versus Particle Index Values - Composite Blend

Based on the linear regression analyses, the aggregate particle characterization tests were ranked according to the highest correlations for each permanent deformation property. These rankings are presented in Table 26. These rankings indicated that the composite aggregate blend and coarse aggregate fraction characterization tests evaluate the permanent deformation properties the best. Of these tests, the Particle Index values produce the strongest relationships. This ranking also indicated that the fine aggregate fraction tests have the weakest relationship to the permanent deformation properties which is contrary to many other findings.

Correlation of AC-20 HMA Properties with Confined Repeated Load Deformation Properties

A summary of the linear regression analyses for the AC-20 HMA mixtures and permanent deformation properties is presented in Table 27. The correlations for the GEPI values were the strongest for each permanent deformation property (permanent strain - R^2 = 0.786, creep modulus - R^2 = 0.793, and slope of creep curve - R^2 = 0.791). This tests ranked the highest for all three permanent deformation properties (Table 27). The results of these strong correlations are shown in Figures 45-47.

Table 27. Rankings for Correlations of AC-20 Mixture Properties with Permanent Deformation Properties

Rank	Permanent strain	Creep modulus	Slope of creep curve
1	GEPI (0.786)	GEPI (0.793)	GEPI (0.791)
2	Marshall Stability (0.563)	Direct Shear Strength (0.710)	Stability/Flow (0.652)
3	Direct Shear Strength (0.553)	Stability/Flow (0.633)	Marshall Stability (0.640)
4	Stability/Flow (0.475)	Indirect Tensile 104°F (0.535)	Direct Shear Strength (0.573)
5	Gyratory Shear Strength (0.282)	Marshall Stability (0.527)	Indirect Tensile 104°F (0.405)
6	Angle of Internal Friction (0.272)	Gyratory Shear Strength (0.508)	Gyratory Shear Strength (0.357)
7	Indirect Tensile 104°F (0.242)	Angle of Internal Friction (0.323)	Angle of Internal Friction (0.315)
8	Marshall Flow (0.232)	Indirect Tensile 77°F (0.224)	Indirect Tensile 77°F (0.295)
9	Indirect Tensile 77°F (0.104)	Marshall Flow (0.093)	Marshall Flow (0.170)

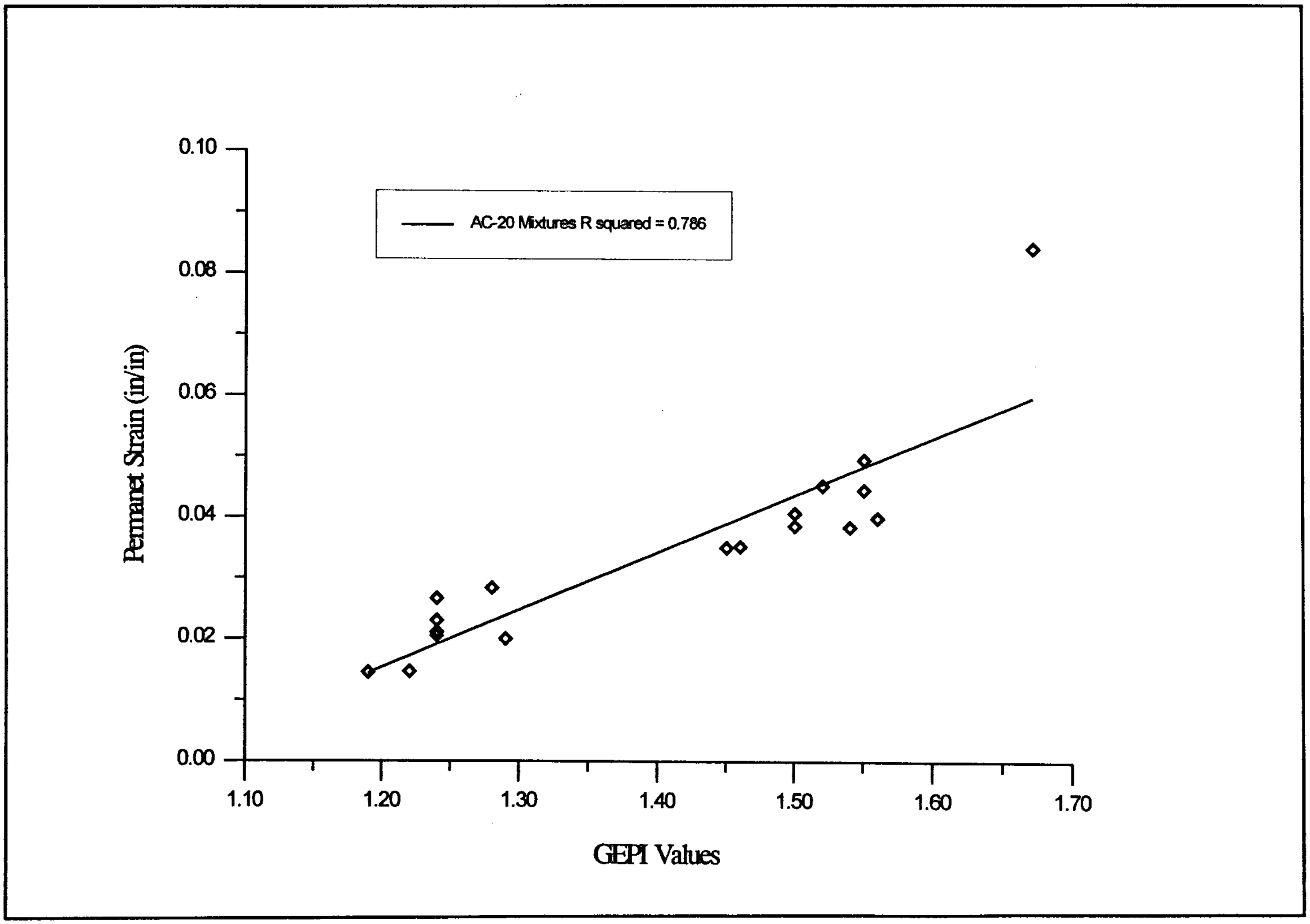


Figure 45. Permanent Strain Values for AC-20 Mixtures versus GEPI Values

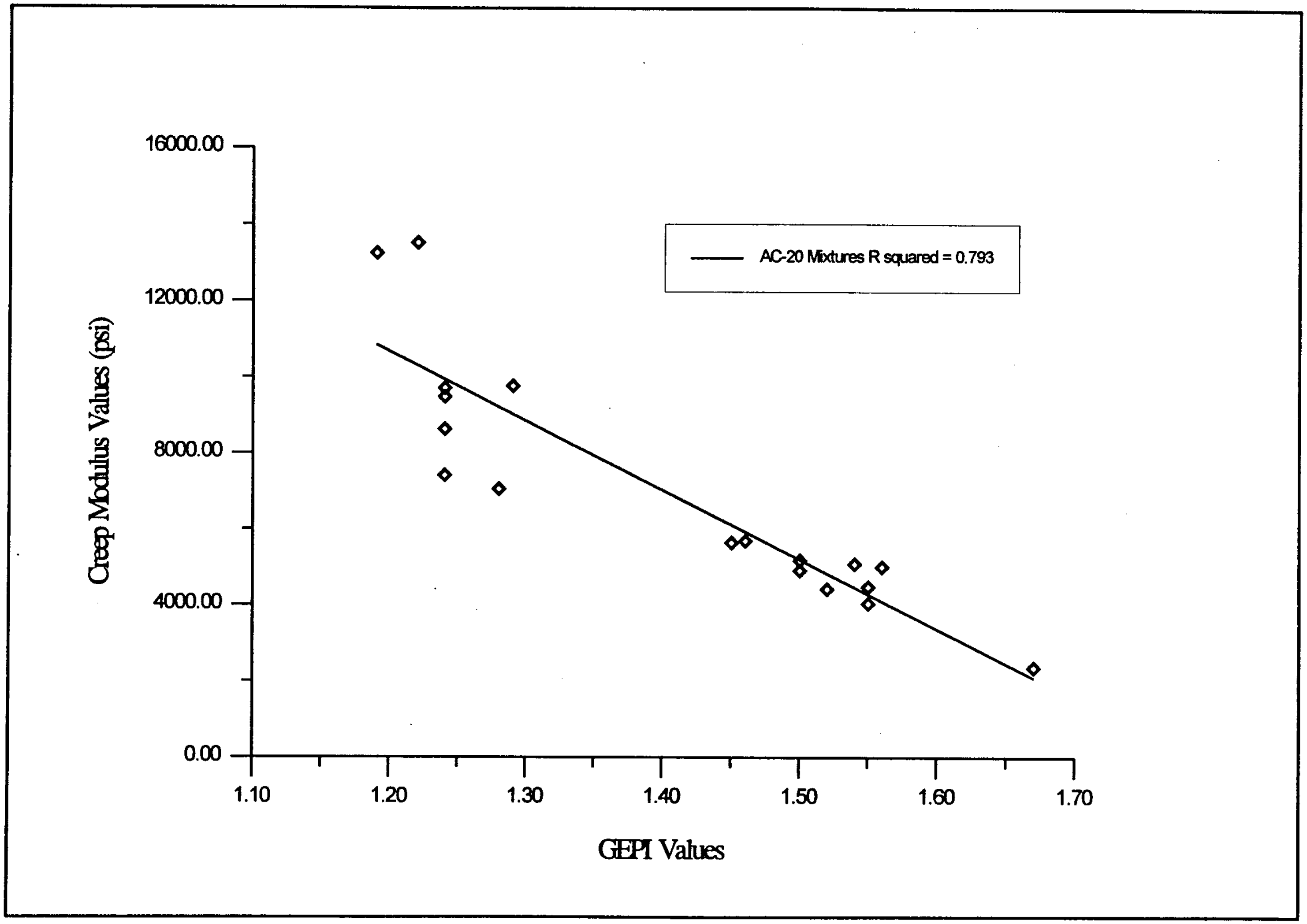


Figure 46. Creep Modulus Values for AC-20 Mixtures versus GEPI Values

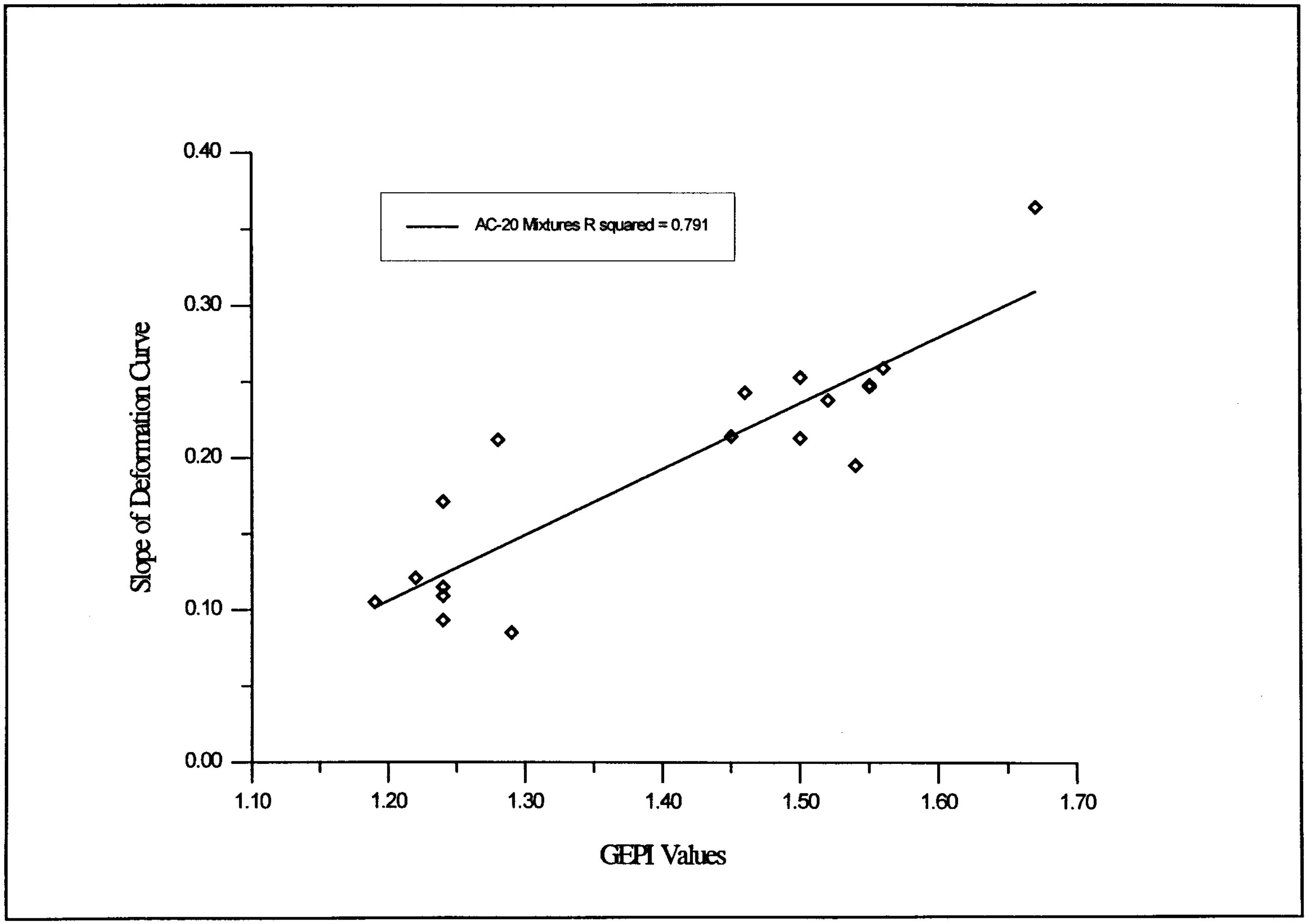


Figure 47. Slope of Deformation Curve Values for AC-20 Mixtures versus GEPI Values

Gyratory Compaction Properties

Gyratory compaction properties have been reported to distinguish between acceptable and unacceptable HMA mixtures. (3,39) The measured gyratory compaction properties included GSI, GEPI, and gyratory shear strength. The GSI value was approximately 1.0 for all HMA mixtures because the air void content was held constant at 4 percent. The GEPI and gyratory shear strength values were measured for each mixture and were correlated with laboratory permanent deformation characteristics in the previous section. The gyratory shear strength values produced weak correlations and trends that were contrary to expected results (uncrushed gravel mixture had higher gyratory shear strength than crushed limestone mixture). The GEPI values produced strong correlations with rutting characteristics, so further investigations were warranted.

As discussed earlier in this report, the GEPI index is a value that indicates the quality (shape and surface texture) of the aggregate in a compacted asphalt mixture. The analysis of this HMA mixture property included correlations with percent crushed particles, amount of natural sand material, and the other aggregate characterization tests to validate GEPI values with known aggregate shape and texture properties.

A summary of the coefficients of determination for the GEPI index and the aggregate particle characterization tests is presented in Table 28. These correlations are separated into composite, coarse, and fine aggregate fractions. The percent crushed particles and the Particle Index test were evaluated for the composite blend. The R^2 value for the correlation with the Particle Index test was very strong (R^2 = 0.790). The Particle Index test and the Modified NAA particle shape and texture test for the coarse aggregate fraction correlated very well with the GEPI values, 0.735 and 0.699 respectively. The

Table 28. Correlation of Gyratory Elasto-Plastic Index Values with Aggregate Particle Characterization Tests

Aggregate Size	Aggregate particle characterization test	Coefficient of determination (R^2)
Composite	Percent Crushed Particles	0.530
	Particle Index	0.790
Coarse Aggregate	Percent Crushed Particles	0.420
	Particle Index	0.735
	Modified NAA As Prepared	0.699
Fine Aggregate	Percent Crushed Particles	0.130
	Natural Sand Content	0.151
	Particle Index	0.168
	NAA-Method A	0.492

correlations for the GEPI values and the fine aggregate particle characterization tests were not very strong and indicated the GEPI value was influenced by the total aggregate blend. These test results indicate the GEPI value is a measure of the composite aggregate blend.

Several observations and trends were observed from the GEPI values. In evaluating the effect of the shape of aggregate gradation curve, the GEPI value did not vary significantly for Mixes A-H. These results were expected because the same aggregate type (crushed limestone) was used in all these mixtures. In evaluating the effect of the percentage of crushed coarse aggregate, the GEPI value did distinguish between the difference in percent crushed coarse particles, as the percentage of uncrushed coarse aggregate increased, the GEPI value increased (Figure 48). Mix I (crushed coarse aggregate) had a GEPI value of 1.46 while Mix Q (uncrushed coarse aggregate) had a GEPI value of 1.55. The amount of natural sand material had the same effect on the GEPI value as did the percentage of crushed coarse aggregate. The GEPI value increased as the amount of natural sand increased. The GEPI values ranged from 1.46 for Mix I (crushed fine aggregate) to 1.56 for Mix M (40 percent natural sand). The most significant difference in GEPI values was between Mix A (crushed limestone) and Mix R (uncrushed gravel), 1.24 to 1.67, respectively.

MODIFIED HMA MIXTURES

This section presents and discusses the results of the preparation and testing of eight selected aggregate blends produced with two polymer modified AC-20 materials. This phase of the laboratory testing was designed to determine the effectiveness of asphalt modification to improve HMA mixtures with substandard aggregate properties. The selected aggregate blends were chosen to determine the benefits of asphalt modification on aggregate type (limestone, gravel), gradation, and percent crushed particles (coarse and fine). The primary emphasis of this phase was to determine if asphalt modification could improve HMA mixtures with poor quality aggregates to provide acceptable pavement performance.

The eight selected aggregate blends and their description are listed in Table 29. A volumetric mix design with gyratory compaction was conducted for each aggregate blend and asphalt binder material (total of 16 mix designs). The optimum asphalt content for each mixture was selected at 4 percent air voids as was done with the AC-20 HMA mixtures. The HMA mixture rutting characteristics were determined by the confined repeated load deformation test.

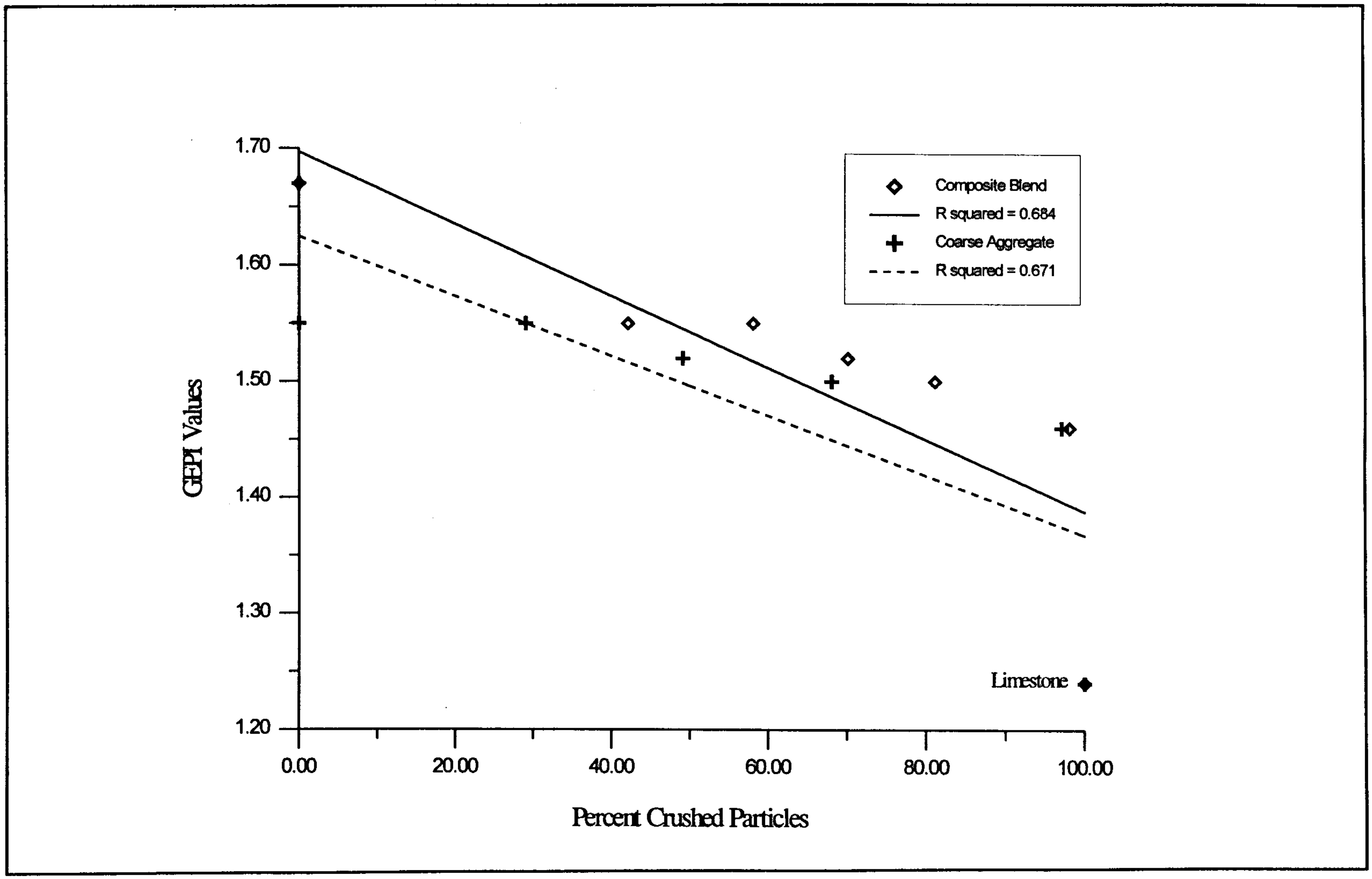


Figure 48. GEPI Values versus Percent Crushed Aggregate - Composite Blend and Coarse Aggregate

Table 29. Selected Aggregate Blends for Modified HMA Mixtures

Mix identification	Description	Composition
A	Center of FAA gradation band	100% crushed limestone
C	Fine side (upper limit) of FAA band	88% crushed limestone 12% natural fine sand
E	Excessive No. 200 material	90% crushed limestone 8% natural fine sand 2% natural coarse sand
I	Center of FAA gradation band	100% crushed gravel
M	Center of FAA band modified with 40% natural sand	60% crushed gravel 40% natural coarse sand
O	Center of FAA gradation band	Coarse 50% crushed gravel 50% uncrushed gravel Fine 100% crushed gravel
Q	Center of FAA gradation band	Coarse 100% uncrushed gravel Fine 100% crushed gravel
R	Center of FAA gradation band	89% uncrushed gravel 6% natural fine sand 5% natural coarse sand

This chapter is organized to present and discuss the results of the SBS modified AC-20 and the LDPE modified AC-20 mixtures. Analysis of these test results included determining the benefits or improvements of asphalt modification on HMA mixtures with poor quality aggregates.

Presentation of Test Results

Volumetric and Marshall Properties

A volumetric mix design was used to determine the optimum asphalt content for the modified mixtures. The compaction temperature for the two AC-20 modified asphalts was increased to 290°F to insure an adequate viscosity of the asphalt binders for compaction of the HMA mixtures. A summary of the Marshall mix properties of the modified mixtures is presented in Tables 30 and 31. These test results include unit weight, theoretical specific gravity, air voids, voids in mineral aggregates, voids filled with asphalt, and the Marshall stability and flow values. The void parameters and gravity values are for an average of 24 specimens while the stability and flow values are for an average of 3 to 5 specimens.

Confined Repeated Load Deformation Properties

Confined repeated load deformation tests were conducted on modified mixtures to determine the improvements of asphalt modification on the rutting characteristics of these mixtures. Theoretically, the stiffer asphalt binders should decrease the rutting potential of asphalt mixtures when tested at 140°F. A summary of the confined repeated load deformation tests are presented in Tables 32 and 33. These test results include deformation or strain values, creep modulus or stiffness values, and the slope of the creep curve plotted on a log-log scale. The confined repeated load deformation test was conducted on a minimum of 3 specimens for each modified mixture and the individual test results are presented in Tables B2 and B3.

Table 30. Summary of Marshall Mix Properties at Optimum Asphalt Content for SBS Modified AC-20 Mixtures

Mix identification	Optimum asphalt content (%)	Bulk specific gravity	Theoretical specific gravity	Voids total mix (%)	Voids in mineral aggregate (%)	Voids filled (%)	Unit weight (pcf)	Stability (lbs)	Flow (0.01 in.)
A	4.7	2.527	2.627	3.8	15.6	75.5	157.7	2323	14.2
C	5.0	2.493	2.591	3.8	16.2	76.6	155.6	2444	13.0
E	4.3	2.523	2.625	3.9	14.6	73.5	157.5	2794	13.3
I	6.7	2.273	2.367	4.0	19.0	79.3	141.9	2350	18.0
M	5.6	2.325	2.417	3.8	16.7	77.1	145.0	1508	10.7
O	6.4	2.277	2.374	4.1	18.5	77.9	142.1	1906	13.5
Q	5.9	2.296	2.390	3.9	17.4	77.4	143.3	2293	13.3
R	4.3	2.357	2.455	4.0	14.0	71.6	147.1	1302	10.0

Table 31. Summary of Marshall Mix Properties at Optimum Asphalt Content for LDPE Modified AC-20 Mixtures

Mix identification	Optimum asphalt content (%)	Bulk specific gravity	Theoretical specific gravity	Voids total mix (%)	Voids in mineral aggregate (%)	Voids filled (%)	Unit weight (pcf)	Stability (lbs)	Flow (0.01 in.)
A	4.7	2.526	2.632	4.0	15.6	74.2	157.6	2495	15.2
C	4.8	2.504	2.605	3.9	15.6	75.2	156.2	2596	14.5
E	4.2	2.530	2.633	3.9	14.3	72.6	157.9	3137	13.8
I	6.5	2.277	2.379	4.3	18.7	77.1	142.1	2089	14.2
M	5.5	2.332	2.426	3.9	16.4	76.4	145.5	1411	10.2
O	6.2	2.292	2.387	4.0	17.8	77.7	143.0	1974	14.5
Q	5.9	2.300	2.395	4.0	17.2	76.8	143.5	1725	12.7
R	4.3	2.365	2.459	3.8	13.7	72.2	147.6	1680	10.2

Table 32. Summary of Confined Repeated Load Deformation Test Data for SBS Modified AC-20 Mixtures

Mix identification	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
A	2.424	4.0	0.0219	0.0219	9132	0.081
C	2.427	3.9	0.0218	0.0218	9174	0.077
E	2.412	4.2	0.0226	0.0226	8850	0.096
I	2.673	4.0	0.0212	0.0212	9434	0.156
M	2.581	4.0	0.0361	0.0361	5540	0.148
O	2.672	4.2	0.0259	0.0258	7722	0.157
Q	2.640	4.1	0.0341	0.0341	5865	0.156
R	2.536	3.9	0.0429	0.0426	4662	0.199

Table 33. Summary of Confined Repeated Load Deformation Test Data for LDPE Modified AC-20 Mixtures

Mix identification	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
A	2.442	4.2	0.0193	0.0193	10362	0.095
C	2.417	3.9	0.0223	0.0223	8969	0.080
E	2.412	4.0	0.0295	0.0295	6780	0.100
I	2.677	4.2	0.0392	0.0399	5102	0.128
M	2.584	3.9	0.0412	0.0411	4854	0.185
O	2.643	4.2	0.0331	0.0330	6042	0.083
Q	2.597	4.0	0.0500	0.0500	4000	0.141
R	2.521	3.8	0.0699	0.0669	2861	0.307

Analysis and Discussion of Test Results

This phase of the laboratory study was designed to determine the effectiveness of asphalt modification to improve the rutting characteristics of HMA mixtures with poor quality aggregates. The analysis of the test results involved determining the benefits or improvements (percent difference from the AC-20 mixtures) that were caused by asphalt modification. The criteria for improvement was considered to be an improvement of the rutting characteristics of the HMA mixtures. Improvement was also considered if a HMA mixture with a stiff asphalt binder produced results equal to or better than that of a control mixture with an AC-20 asphalt binder.

Benefits of Asphalt Modification

The benefits or improvements produced by the asphalt modification were determined using the HMA mixture's permanent deformation properties. The rutting characteristics of the modified HMA mixtures were determined from the results of the confined repeated load deformation test. The benefits or improvements of the asphalt modification on the rutting characteristics of the HMA mixtures were evident in the permanent strain values, creep modulus values, and the slope of the deformation curve. The test results indicated that the two polymer modified AC-20 binders did have a significant effect on the rutting characteristics. Overall, the SBS modified AC-20 binder produced the greatest improvements in these HMA mixtures.

The changes in the permanent strain values caused by the asphalt modification are presented in Table 34 and shown graphically in Figure 49. The permanent strain values for the SBS modified mixtures improved for all the mixtures except Mixes A and C. The SBS modified mixtures produced a reduction in permanent strain values ranging from 9.5 to

49.5 percent. Mix I (crushed gravel) was improved enough by the SBS modification to equal the strain values produced by Mix A (crushed limestone).

Mixes M, O, and Q were also improved by SBS modification to approximately equal strain levels produced in the AC-20 control mixtures (Mix I). The LDPE modified AC-20 binder also improved Mix O so that this mixture had lower strain levels than Mix I with AC-20.

The changes produced by asphalt modification on the creep modulus values are presented in Table 35 and shown graphically in Figure 50. As with the permanent strain values, the SBS modified AC-20 binder produced the greatest improvements in creep modulus values. These improvements in the creep modulus values ranged from 10.8 to 97.9 percent. Mix I (SBS modified) was improved enough to equal Mix A (AC-20). Mixes O and Q were improved enough by the SBS modification to equal or surpass the control mixture (Mix I - AC 20) with values of 5865 and 7722 psi, respectively. Mix O modified with the LDPE binder was also improved enough to surpass the control mixture (Mix I - AC 20) with a creep modulus value of 6042 psi.

The slope of the creep curve or the rate of rutting value was affected by the asphalt modification. The SBS and LDPE modified AC-20 binders significantly reduced the value for slope of the creep curve for each mixture. The positive reduction in slope values caused by the stiff asphalt binders is presented in Table 36 and shown graphically in Figure 51. It is evident from this data that the modified AC-20 mixtures had a lower rate of potential rutting than the unmodified AC-20 mixtures of the same aggregate type and gradation.

Based on the findings of this analysis, the following conclusions about asphalt modification on HMA mixtures with poor quality aggregate are listed below:

1. Asphalt modification had little effect on permanent strain and creep modulus values for limestone aggregate mixtures (Mixes A, C, and E).

2. SBS modification improved the rutting characteristics of all the gravel mixtures (Mixes I, M, O, Q, and R).

3. SBS modification improved the permanent strain and creep modulus values of the 100 percent crushed gravel mixture (Mix I) enough to equal the values of the 100 percent crushed limestone mixture (Mix A).

4. Asphalt modification did not improve rutting characteristics of the crushed gravel mixture with high natural sand content (Mix M).

5. SBS modification significantly improved the gravel mixtures with various percentages of crushed coarse aggregate (Mixes O, Q, and R).

6. Asphalt modification reduced the rate of rutting for all mixtures.

Table 34. Permanent Strain Values for Modified HMA Mixtures

Mix identification	AC-20	AC-20 + SBS	Percent difference	AC-20 + LDPE	Percent difference
A	0.0211	0.0219	+ 3.8	0.0193	- 8.5
C	0.0205	0.0218	+ 6.3	0.0223	+ 8.8
E	0.0266	0.0226	- 15.0	0.0295	+ 10.9
I	0.0352	0.0212	- 39.8	0.0389	+ 10.5
M	0.0399	0.0361	- 9.5	0.0411	+ 3.0
O	0.0452	0.0258	- 41.9	0.0330	- 27.0
Q	0.0495	0.0341	- 31.1	0.0500	+ 1.0
R	0.0843	0.0426	- 49.5	0.0699	- 17.1
Positive (+) difference - increased rutting potential.					

Table 35. Creep Modulus Values for Modified HMA Mixtures

Mix identification	AC-20	AC-20 + SBS	Percent difference	AC-20 + LDPE	Percent difference
A	9479	9132	- 3.7	10362	+ 9.3
C	9709	9174	- 5.5	8969	- 7.4
E	7407	8850	+ 19.5	6780	- 8.5
I	5682	9434	+ 66.0	5102	- 10.2
M	5000	5540	+ 10.8	4854	- 2.9
O	4415	7722	+ 74.9	6042	+ 36.9
Q	4040	5865	+ 45.2	4000	- 1.0
R	2356	4662	+ 97.9	2861	+ 21.4
Positive (+) difference - decreased rutting potential.					

Table 36. Slope of Log-Log Creep Curve Values for Modified HMA Mixtures

Mix identification	AC-20	AC-20 + SBS	Percent difference	AC-20 + LDPE	Percent difference
A	0.109	0.081	- 25.7	0.095	- 12.8
C	0.093	0.077	- 17.2	0.080	- 14.0
E	0.171	0.096	- 43.9	0.100	- 41.5
I	0.243	0.156	- 35.8	0.128	- 47.3
M	0.259	0.148	- 42.9	0.185	- 28.6
O	0.238	0.157	-34.0	0.083	-65.1
Q	0.247	0.156	- 36.8	0.141	- 42.9
R	0.365	0.199	- 45.5	0.307	- 15.9
Negative (-) difference - decreased rutting potential					

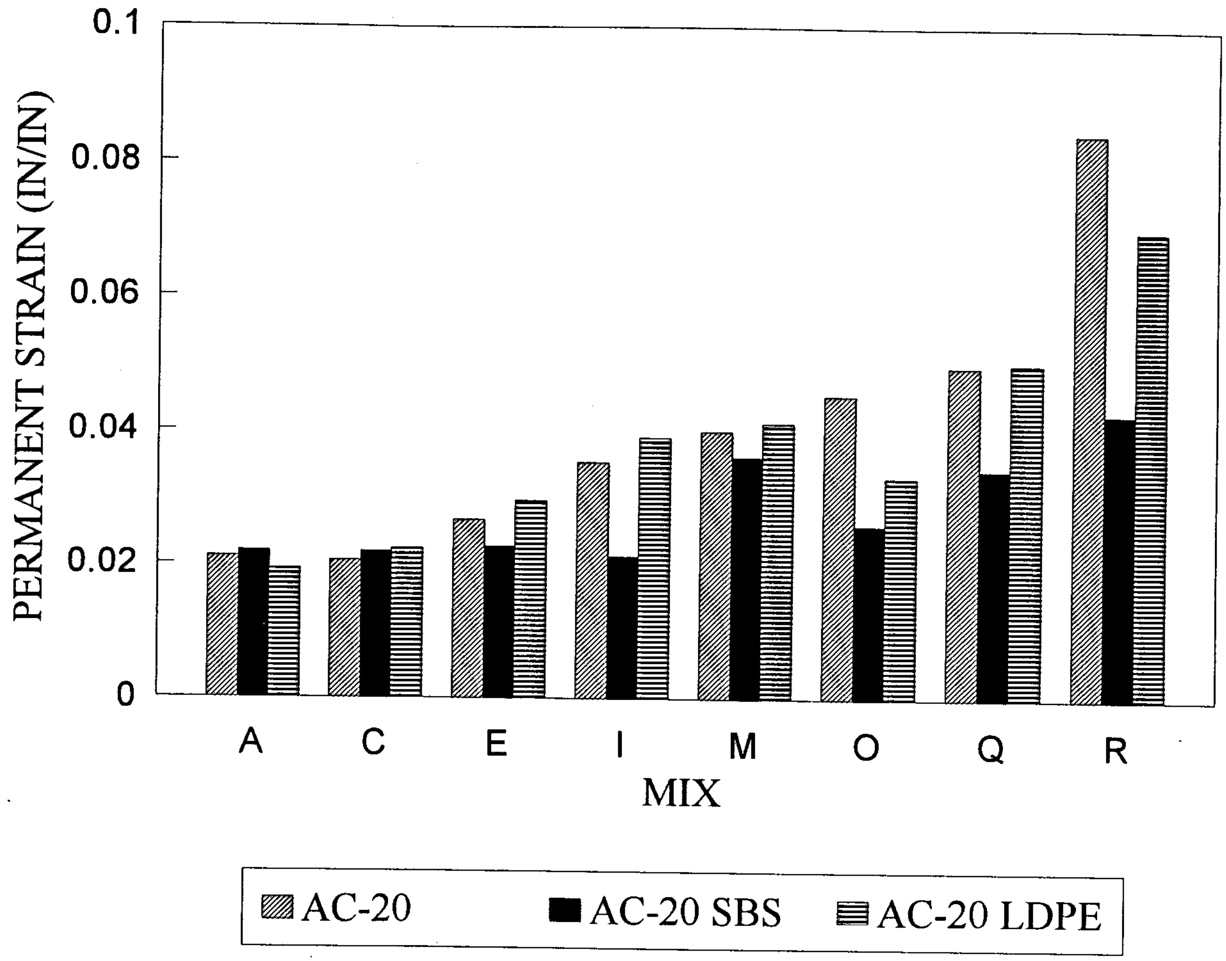


Figure 49. Effect of Asphalt Modification on Permanent Strain Values

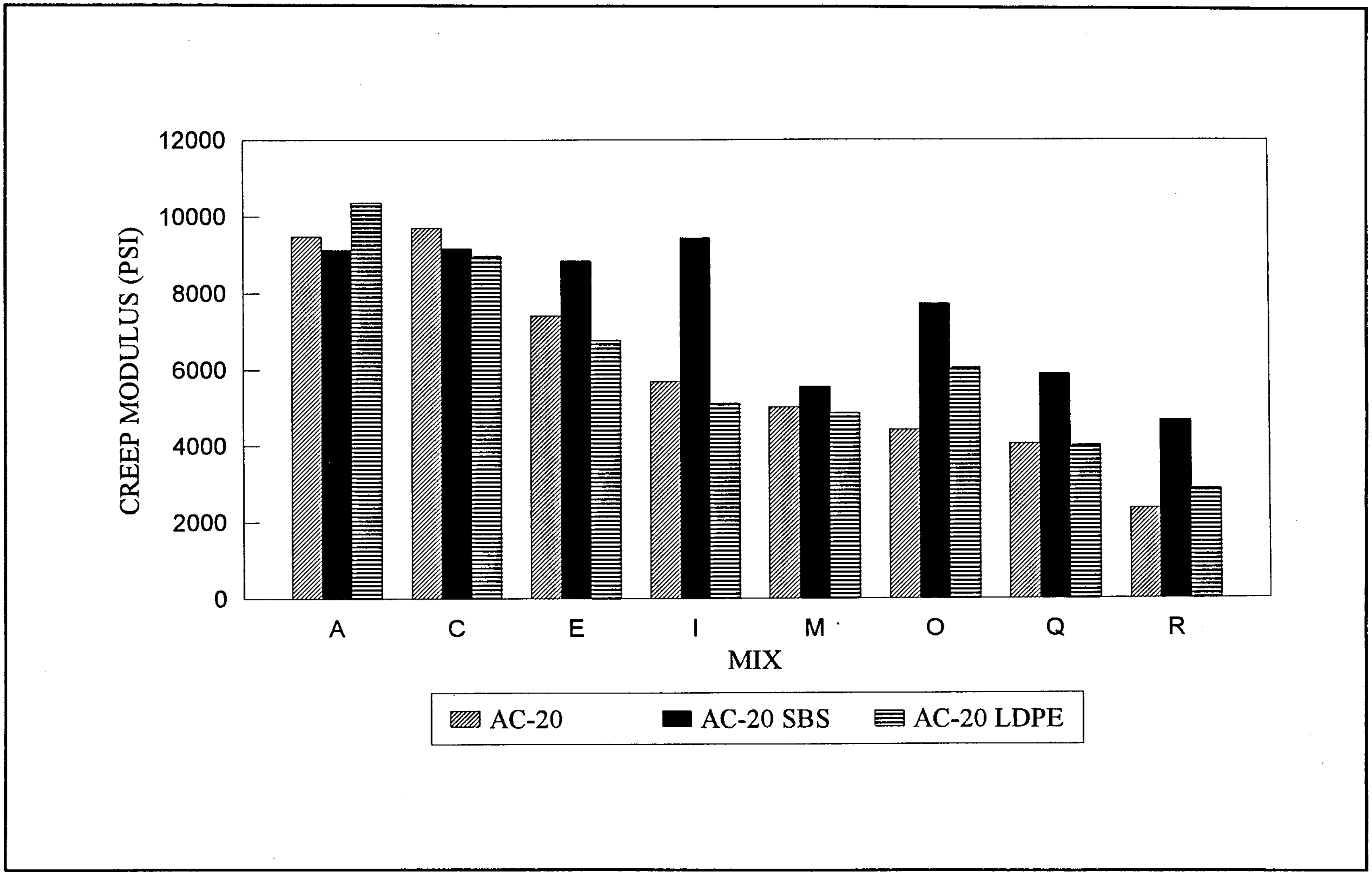


Figure 50. Effect of Asphalt Modification on Creep Modulus Values

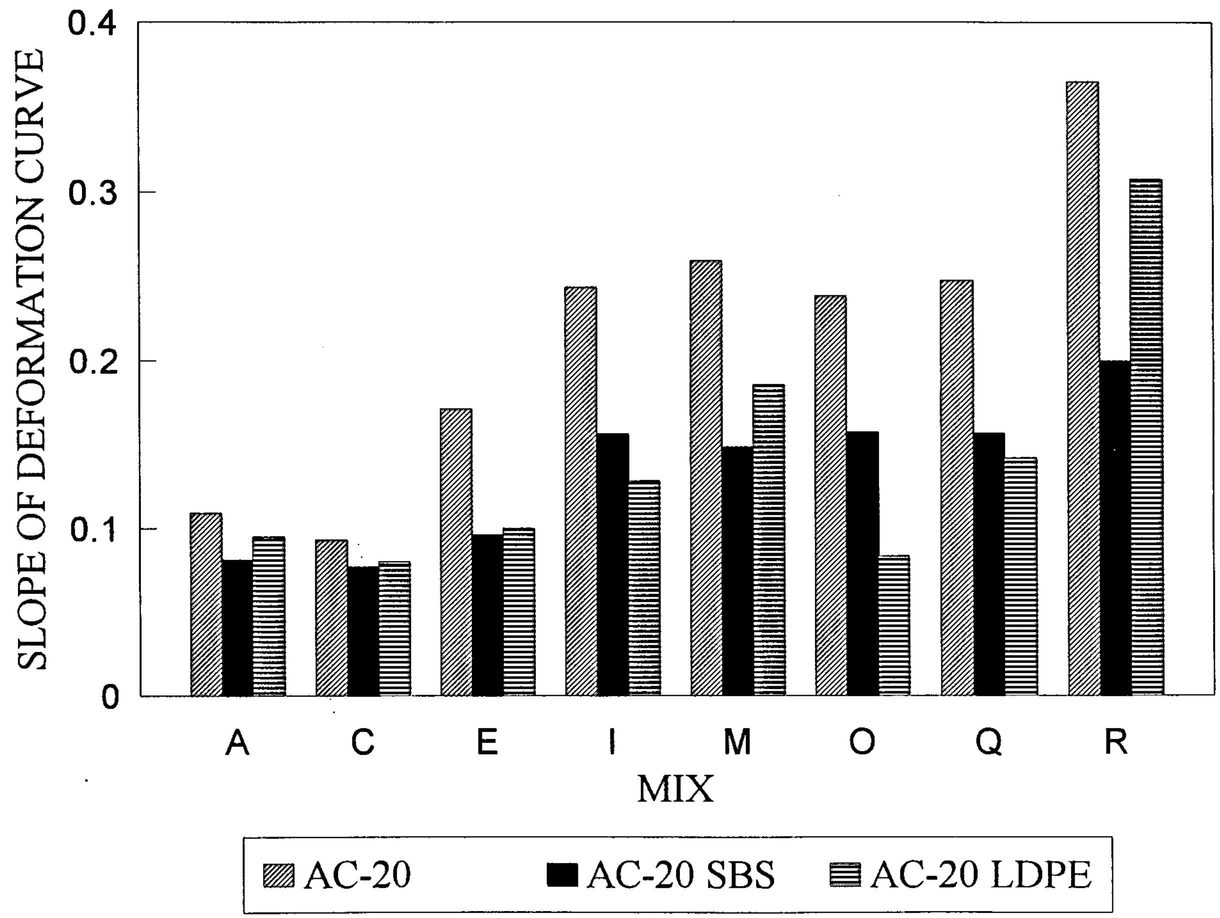


Figure 51. Effect of Asphalt Modification on Slope of Log-Log Creep Curve

CHAPTER VI FIELD EVALUATION

The field evaluation outlined in the Plan of Study was conducted to evaluate HMA mixtures with different aggregate properties under actual traffic loading conditions. The field evaluation also evaluated the benefits of asphalt modification to improve rutting characteristics of HMA mixtures with substandard aggregates. The field evaluation was conducted in four phases: (1) selection and construction of ten test items, (2) evaluation of test item HMA mixtures, (3) trafficking test items, and (4) evaluation of performance.

SELECTION AND CONSTRUCTION OF FIELD TEST ITEMS

As a part of the FAA research project, "Marginal Aggregates in Flexible Pavements," a full scale test section was constructed and trafficked to evaluate substandard aggregate materials in HMA mixtures. (75) These aggregate properties included gradation, percent crushed coarse particles, and natural sand content. Based on the findings of the laboratory evaluation, seven aggregate blends were selected to determine the effects of aggregate properties on permanent deformation. A SBS modified AC-20 asphalt binder was used with five aggregate blends to evaluate the benefits of asphalt modification on HMA mixtures with substandard aggregates. The descriptions of the ten field test items are presented in Table 37.

Table 37. Description of Test Item Aggregate Blends

Identification	Description	Composition	Asphalt binder
1	Center of FAA gradation band	20% crushed limestone #458 28% crushed limestone #56 37% crushed limestone screenings 15% mason sand	AC-20
2	Upper limit of FAA gradation band	8% crushed limestone #458 20% crushed limestone #56 47% crushed limestone screenings 25% mason sand	SBS-modified AC-20
3	Upper limit of FAA gradation band with excessive No. 200 material	13% crushed limestone #458 20% crushed limestone #56 62% crushed limestone screenings 5% mason sand	AC-20
4	Center of FAA gradation band modified with 20% natural sand	25% crushed limestone #458 18% crushed limestone #56 21% crushed limestone screenings 16% crushed gravel screenings 20% concrete sand	AC-20
5	Center of FAA gradation band modified with 20% natural sand	25% crushed limestone #458 18% crushed limestone #56 21% crushed limestone screenings 16% crushed gravel screenings 20% concrete sand	SBS-modified AC-20

(Sheet 1 of 2)

Table 37. Description of Test Item Aggregate Blends (Concluded)

Identification	Description	Composition	Asphalt binder
6	Center of FAA gradation band modified with 40% natural sand	25% crushed limestone #458 15% crushed limestone #56 20% crushed limestone screenings 40% concrete sand	AC-20
7	Center of FAA gradation band modified with 40% natural sand	25% crushed limestone #458 15% crushed limestone #56 20% crushed limestone screenings 40% concrete sand	SBS-modified AC-20
8	Center of FAA gradation Coarse - 100% uncrushed gravel Fine - 100% limestone and crushed gravel	30% crushed limestone screenings 45% crushed gravel screenings 25% uncrushed coarse gravel	SBS-modified AC-20
9	Center of FAA gradation band Coarse - 50% uncrushed gravel, 50% crushed limestone Fine - 100% limestone and crushed gravel	12% crushed limestone #458 30% crushed limestone screenings 45% crushed gravel screenings 13% uncrushed coarse gravel	AC-20
10	Center of FAA gradation band Coarse - 50% uncrushed gravel, 50% crushed limestone Fine - 100% limestone and crushed gravel	12% crushed limestone #458 30% crushed limestone screenings 45% crushed gravel screenings 13% uncrushed coarse gravel	SBS-modified AC-20

(Sheet 2 of 2)

Seven aggregate stockpiles were used in various combinations to produce the test item aggregate blends. The stockpiles consisted of crushed limestone (#458, #56, and screenings), crushed gravel screenings, uncrushed coarse gravel, and two natural sand materials (concrete and mason). The gradation, specific gravity, and absorption values of each stockpile material are summarized in Table A5. The test item aggregate blends were produced with the stockpile percentages listed in Table 37 in order to evaluate the effects of gradation, amount of natural sand in the aggregate blend, percent of crushed coarse particles, and asphalt modification. The benefits of asphalt modification were evaluated with comparisons of identical aggregate blends produced with AC-20 and SBS-modified AC-20 and substandard aggregate blends produced with SBS-modified AC-20. The comparisons for each of these variable groups are presented in Table 38.

Table 38. Evaluations of Test Item HMA Mixtures

Variables	Item number
Effect of gradation	1, 3, 4, 6
Effect of percent crushed coarse particles	1, 8, 9
Effect of amount of natural sand	1, 4, 6
Effect of asphalt modification	
Identical aggregate blends	4 and 5, 6 and 7, 9 and 10
Substandard aggregate blends	1, 2, 5, 7, 8, 10

The test section was constructed as an overlay on top of an existing test section located at the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. The existing pavement was structurally sound and was designed to carry military cargo aircraft (C141) loads. This pavement section provided a structurally adequate base for the HMA test items and insured that pavement deformation would occur in the surface layers as densification or plastic flow. A layout of the ten test items is illustrated in Figure 52. The typical cross section of the test section is illustrated in Figure 53.

The test section was constructed by APAC-Mississippi in two phases. First, a 2.5 in. intermediate layer was placed over the entire test area (65 ft by 250 ft). This HMA mixture was composed of crushed limestone (85 percent), mason sand (15 percent), and AC-30 binder. A summary of the HMA mixture properties is listed in Tables 39 and 40. This layer of HMA provided a dense, smooth foundation for the test items. The test section was produced, placed, and compacted using conventional HMA procedures and techniques. Each test item consisted of approximately 50 tons of material and was placed on an area 25 ft by 40 ft. The thickness of each test item was approximately 2.5 in.

EVALUATION OF TEST ITEM HMA MIXTURES

A sample of plant-mixed HMA material was obtained from loaded asphalt trucks for each test item and evaluated to characterize the HMA mixtures. The laboratory evaluation of the plant-mixed HMA material focused on characterizing the aggregate and the HMA mixture properties. The aggregate characterization tests included gradation, percent crushed particles, natural sand content, NAA and modified NAA particle shape and texture, direct shear, and ASTM C 29 (shovel method). The HMA mixtures were evaluated with volumetric properties, Marshall stability and flow, gyratory compaction properties, direct shear strengths, and confined repeated load deformation properties.

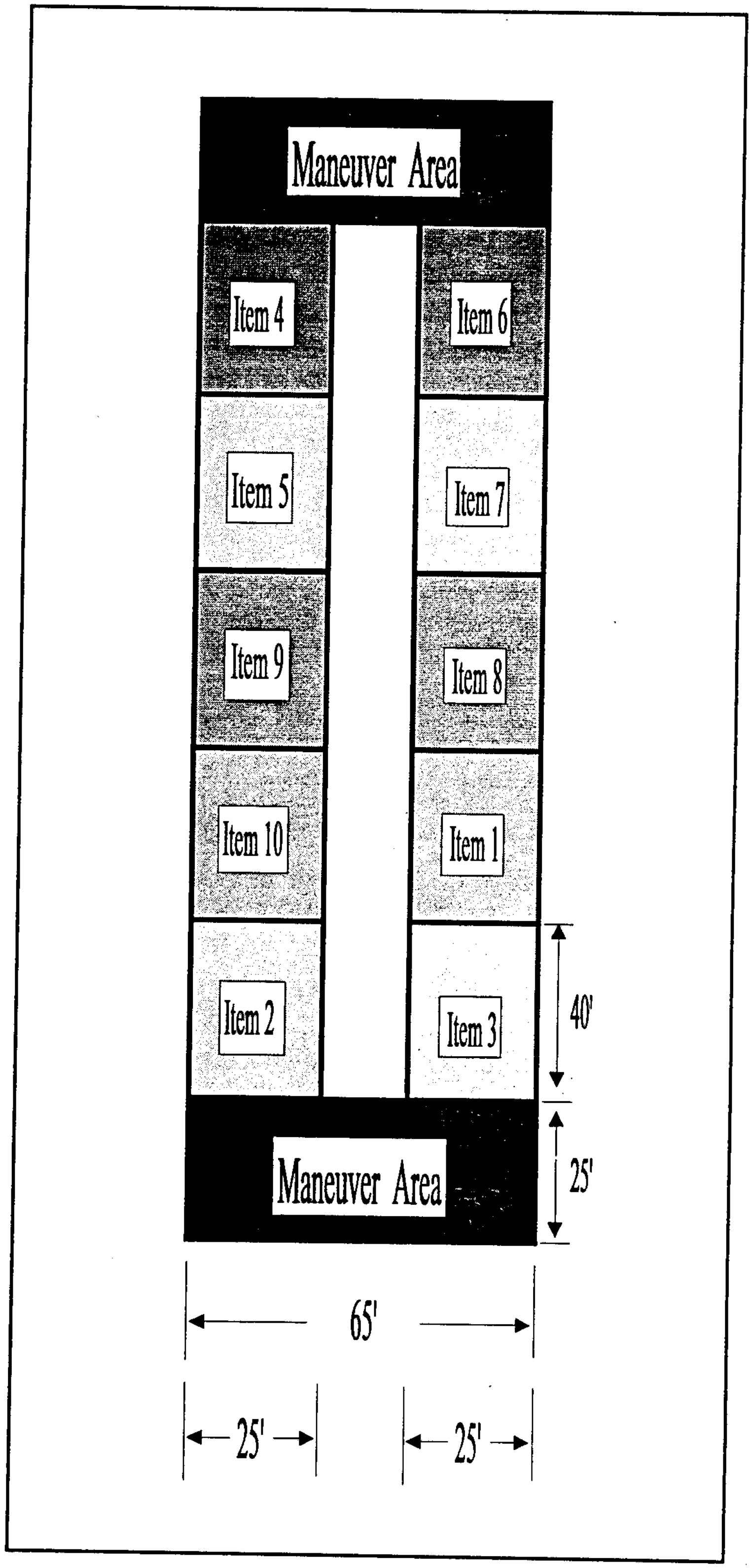


Figure 52. Layout of Field Test Items

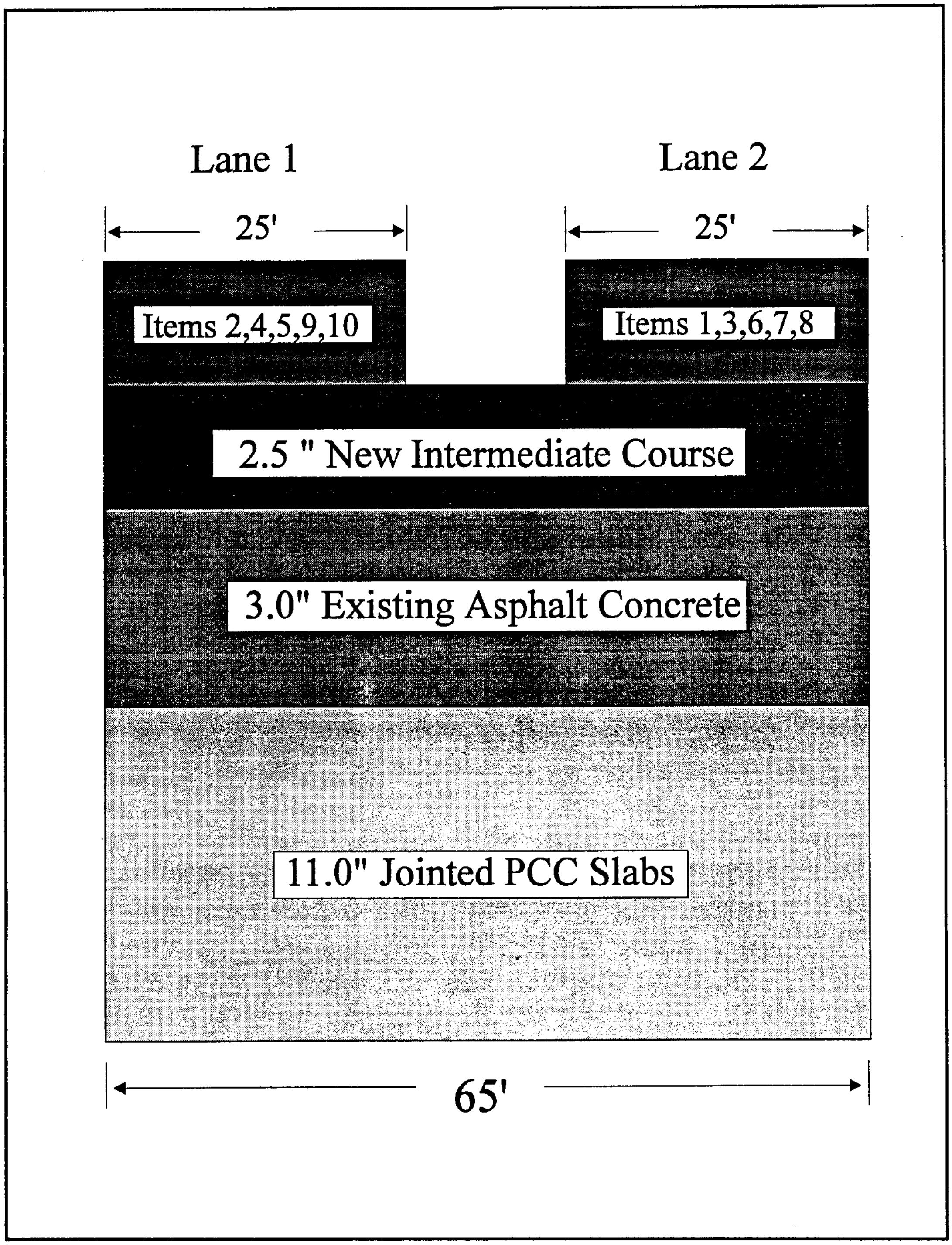


Figure 53. Typical Cross Section of Test Section

Table 39. Aggregate Gradation for Intermediate Course HMA Mixture

Sieve size	FAA limits	Result
3/4 in.	100	100
1/2 in.	79-99	89.2
3/8 in.	68-88	80.2
No. 4	48-68	58.1
No. 8	33-53	37.0
No. 16	20-40	27.4
No. 30	14-30	23.1
No. 50	9-21	10.3
No. 100	6-16	7.1
No. 200	3-6	5.8

Table 40. Marshall Mix Properties for Intermediate Course HMA Mixture

Property	FAA requirements	Result
Stability, lbs (minimum)	2150	2100
Flow, 0.01 in.	10-14	10
Air voids, %	2.8 - 4.2	3.8
Voids in mineral aggregate % (minimum)	14	14.3
Voids filled, %	65-75	75

Aggregate Characterization

This section presents the results of the aggregate characterization tests conducted on the extracted test item aggregates. The aggregate characterization tests determined the shape of the gradation curve and quantified the aggregate particle shape and texture characteristics. Aggregate gradations are presented in Table 41. Table 42 presents the percentages of crushed particles as determined by visual inspection for the composite blend, coarse and fine aggregate fractions. The natural sand content of each material was determined from cold feed bin percentages. The coarse aggregate fraction of each test item was characterized with the modified NAA particle shape and texture and ASTM C 29 (shovel) test methods. These tests for the coarse aggregates were conducted on the minus 3/4 in. to No. 4 sieve material. The uncompacted void contents for these two methods are presented in Table 43. The fine aggregate fraction (minus No. 4 sieve) of each test item was characterized by the NAA particle shape and texture and direct shear test methods. The test results from these fine aggregate tests are presented in Table 44.

HMA Mixture Evaluation

This section presents the results of the HMA mixture evaluation tests on the plant-mixed HMA material. These mixture tests were conducted to determine the HMA mixture's strength and permanent deformation properties. HMA material from each test item were compacted with the Gyratory Testing Machine to produce Marshall size specimen (4 in. diameter and 2.5 in. thick). The compacted specimen were evaluated to determine

Table 41. Aggregate Gradations for Test Section HMA Mixtures

Sieve sizes	Percent Passing									
	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10
3/4 in.	100	100	100	100	100	100	100	100	100	100
1/2 in.	94.0	95.3	92.7	92.9	92.3	92.9	90.9	85.7	91.3	86.3
3/8 in.	86.4	89.0	86.6	81.0	83.6	85.2	82.8	79.6	86.1	80.9
No. 4	69.9	75.4	72.2	65.4	66.3	70.3	67.2	68.8	78.0	73.5
No. 8	44.5	50.8	42.0	47.0	44.3	54.7	50.1	47.2	55.0	54.4
No. 16	30.4	37.2	23.6	36.6	31.8	46.7	42.2	29.3	35.5	35.9
No. 30	23.9	30.6	16.7	27.3	25.0	38.0	34.6	20.5	25.2	25.8
No. 50	9.1	11.4	10.1	6.0	8.5	6.7	7.5	10.8	10.2	12.1
No. 100	5.6	6.5	8.0	2.5	4.7	1.9	2.5	7.3	5.6	7.1
No. 200	4.5	5.2	6.6	1.9	3.4	1.3	1.6	5.8	3.6	4.8

Table 42. Percent Crushed Particles and Natural Sand Content for Test Section HMA Mixtures

Item number	Percent crushed particles with at least two fractured faces			Natural sand content
	Composite gradation	Coarse aggregate fraction	Fine aggregate fraction (*)	
1	85	99	79	15
2	75	100	67	25
3	94	98	93	5
4	79	96	69	20
5	78	95	69	20
6	57	95	41	40
7	57	92	40	40
8	72	11	100	0
9	88	47	100	0
10	88	55	100	0

(*) Down to No. 30 sieve

Table 43. Uncompacted Void Contents for Coarse Aggregate Fraction

Item number	Modified NAA Method 1 (%)	ASTM C 29 Method 1 (%)
1	46.9	45.5
2	47.3	45.5
3	46.9	45.4
4	46.7	45.0
5	46.9	45.1
6	47.2	45.9
7	46.8	45.6
8	44.8	42.8
9	44.1	42.5
10	42.2	40.8

Table 44. Test Results for Fine Aggregate Fraction

Item number	NAA Method A (%)	NAA Method C (%)	Direct shear (ϕ)
1	42.6	36.9	40.5
2	40.0	34.7	39.0
3	44.5	39.3	47.5
4	40.6	34.5	36.0
5	41.4	35.6	37.0
6	38.6	34.4	29.5
7	39.3	33.5	30.5
8	42.5	37.6	43.5
9	42.2	37.4	40.5
10	41.9	36.2	42.0

Marshall and volumetric properties (Table 45), gyratory compaction properties (Table 46), direct shear results (Table 47), and confined repeated load deformation test results (Table 48). Three field cores (4 in. diameter) were also taken from each test item and evaluated with the confined repeated load deformation test. The results of these tests are presented in Table 49. All the test items confined repeated load deformation test results are presented in Tables B4 and B5.

DESCRIPTION OF TRAFFIC

Traffic tests were conducted from June to October 1994 to allow trafficking to take place during high ambient temperatures and pavement surface temperatures. The pavement surface temperature ranged between 75°F and 140°F during the traffic tests. The traffic tests were conducted with a load cart assembly that simulated aircraft loads and tire pressures. The load cart was assembled with a single aircraft tire (12 in. wide) with a load of 40,000 lbs and a contact pressure of 200 psi. The test traffic was applied by driving the load cart assembly forward and then in reverse over the entire length of the test section (1 pass). The lateral traffic pattern was applied with a distribution shown in Figure 54. The traffic lane for each test item was 60 in. wide with five wheel paths. A total of 12,000 passes was applied to each test item.

Table 45. Summary of Volumetric and Marshall Properties for Test Section Items - Lab Compacted

Item number	Extracted asphalt content (%)	Bulk specific gravity	Theoretical specific gravity	Voids total mix (%)	Voids in mineral aggregate (%)	Voids filled (%)	Unit weight (pcf)	Stability (lbs)	Flow (0.01 in.)
1	4.2	2.422	2.533	4.4	14.3	69.2	151.1	2,081	7.7
2	4.9	2.471	2.498	2.4	14.1	83.0	152.1	2,389	11.0
3	4.8	2.400	2.515	4.6	15.8	70.9	149.8	1,971	8.7
4	4.4	2.347	2.514	6.6	16.7	60.5	146.5	874	6.7
5	5.0	2.427	2.484	2.3	14.2	83.6	151.4	1,980	10.3
6	5.2	2.298	2.475	7.2	18.8	61.7	143.4	369	5.3
7	4.9	2.362	2.492	5.2	16.5	68.5	147.4	743	6.8
8	5.7	2.341	2.425	3.5	16.6	78.9	146.1	1,950	18.7
9	6.1	2.343	2.420	3.2	17.1	81.3	146.2	1,324	9.5
10	6.1	2.355	2.413	2.4	16.5	85.5	147.0	1,928	15.3

Table 46. Summary of Gyratory Compaction Properties for Test Section Items

Item number	Thickness (in.)	Gyratory stability index (GSI)	Gyratory elasto plastic index (GEPI)	Gyratory shear strength (psi)
1	2.503	0.99	1.28	149
2	2.471	1.00	1.40	147
3	2.544	1.00	1.20	132
4	2.580	0.98	1.45	163
5	2.490	0.99	1.40	152
6	2.623	0.97	1.61	156
7	2.550	0.97	1.47	157
8	2.588	0.99	1.38	147
9	2.584	0.99	1.43	158
10	2.563	1.02	1.36	136

Table 47. Summary of Direct Shear Data for Test Section HMA Mixtures

Item number	Angle of internal friction (ϕ)	Cohesion Y-axis intercept (psi)	Shear strengths at normal stress levels		
			100 psi (psi)	200 psi (psi)	300 psi (psi)
1	13.7	48.5	73.4	96.2	122.2
2	17.5	58.5	91.8	118.3	154.9
3	15.5	52.1	80.3	106.5	135.9
4	15.9	20.9	50.3	76.1	107.3
5	17.1	44.2	77.4	100.6	138.8
6	17.1	35.7	49.5	61.8	76.3
7	11.7	30.9	53.1	69.3	94.5
8	13.9	50.1	76.1	96.9	125.5
9	13.5	41.1	65.4	88.7	113.5
10	14.7	51.2	78.5	101.5	130.9

Table 48. Summary of Confined Repeated Load Deformation Test Data for Test Items - Lab Compacted

Item number	Asphalt type	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
1	AC-20	2.506	4.4	0.0194	0.0194	10,309	0.146
2	AC-20 + SBS	2.466	2.4	0.0216	0.0216	9,259	0.092
3	AC-20	2.568	4.6	0.0289	0.0289	6,920	0.199
4	AC-20	2.579	6.6	0.0179	0.0178	11,173	0.099
5	AC-20 + SBS	2.479	2.3	0.0217	0.0216	9,217	0.095
6	AC-20	2.633	7.2	0.0248	0.0248	8,065	0.082
7	AC-20 + SBS	2.549	5.2	0.0195	0.0195	10,256	0.054
8	AC-20 + SBS	2.589	3.5	0.0208	0.0207	9,615	0.145
9	AC-20	2.575	3.2	0.0212	0.0212	9,434	0.157
10	AC-20 + SBS	2.561	2.4	0.0384	0.0383	5,208	0.329

Table 49. Summary of Confined Repeated Load Deformation Test Data for Test Items - Field Compacted

Item number	Asphalt type	Thickness (in.)	Inplace Voids	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
1	AC-20	2.896	9.5	0.0270	0.0270	7,407	0.121
2	AC-20 + SBS	2.645	7.5	0.0401	0.0401	4,988	0.123
3	AC-20	2.483	9.9	0.0584	0.0583	3,425	0.172
4	AC-20	2.572	7.4	0.0249	0.0249	8,032	0.123
5	AC-20 + SBS	2.705	5.7	0.0315	0.0315	6,349	0.126
6	AC-20	2.664	9.4	0.0513	0.0513	3,899	0.092
7	AC-20 + SBS	2.740	7.8	0.0406	0.0406	4,926	0.106
8	AC-20 + SBS	2.654	6.3	0.0616	0.0616	3,247	0.123
9	AC-20	2.753	8.3	0.0522	0.0521	3,831	0.136
10	AC-20 + SBS	2.316	7.5	0.0472	0.0471	4,237	0.184

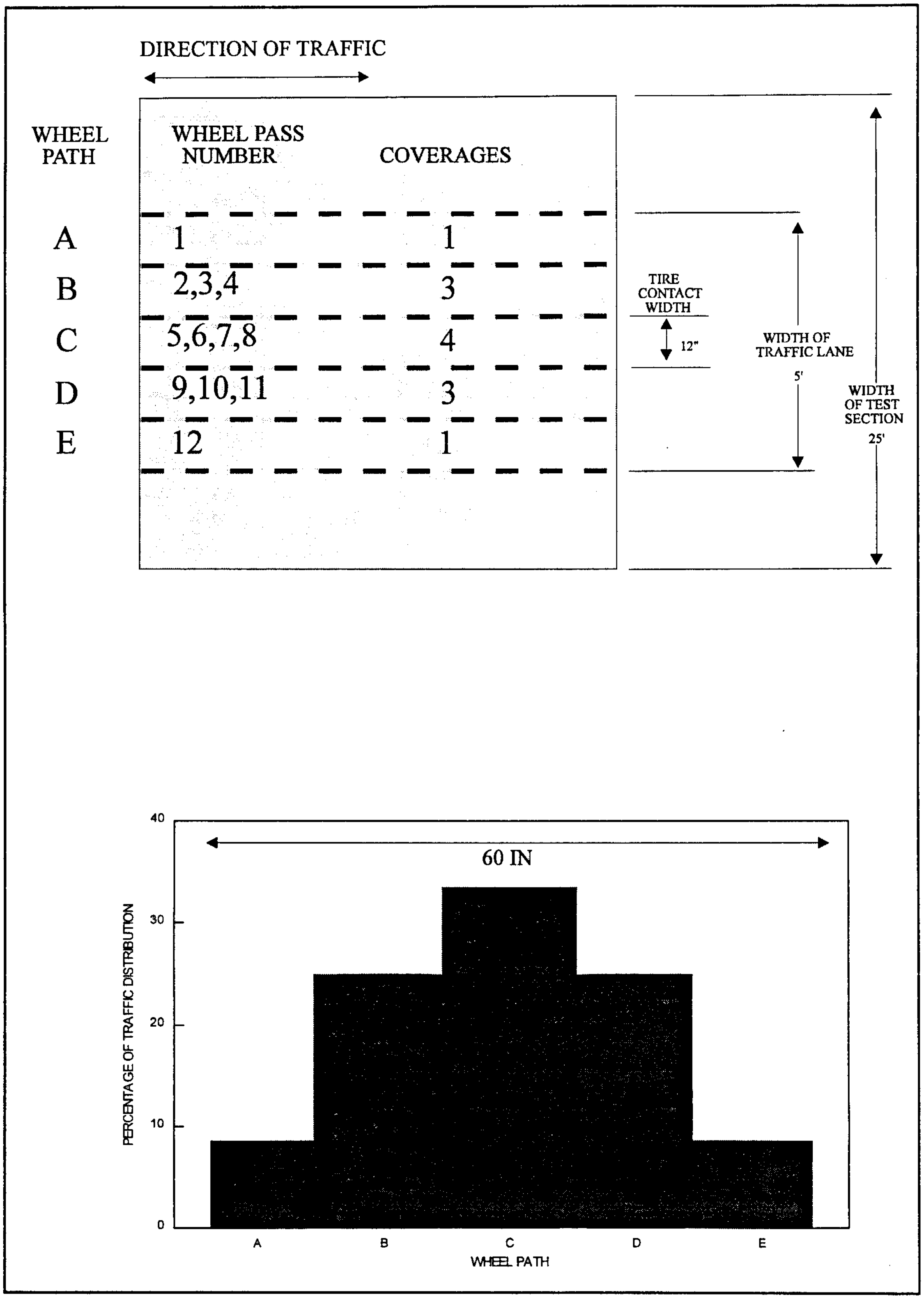


Figure 54. Traffic Pattern Distribution

PERFORMANCE OF TEST ITEMS

The focus of this study was on rutting of HMA mixtures, and the performance of the test items was based on rut depth measurements. Rut depth measurements were taken at various intervals and at the completion of trafficking. Measurements were taken transversely across the traffic lane of each test item. Rut depth measurements were made by placing a 12-ft metal straightedge flat across the test item and measuring the maximum rut depth with a ruler (Figure 55). This rut depth included both permanent deformation caused by densification and plastic flow.

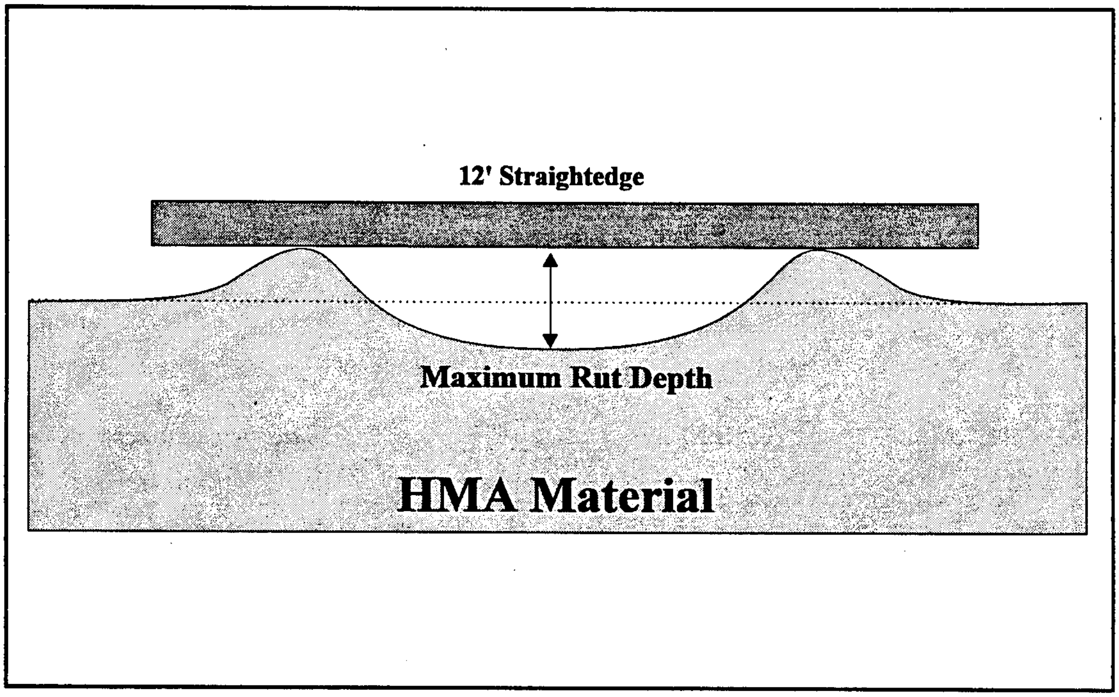


Figure 55. Schematic of Rut Depth Measurement with Straightedge

The rut depth measurements for each test item at various traffic levels are presented in Table 50. Rutting in HMA pavements is generally characterized by the maximum depth of the deformation or by the rate at which the deformation occurred (rutting rate). The rut depth values after 12,000 passes of the load cart are presented in Table 51 and shown graphically in Figure 56.

ANALYSIS AND DISCUSSION OF FIELD EVALUATION

The field evaluation was conducted to evaluate HMA mixtures under actual traffic loading conditions and to determine which aggregate and/or HMA mixture properties influenced the amount of rutting. The laboratory test results for these test section mixtures indicated that the plant-mixed HMA mixtures were not as consistent as the lab-produced HMA mixtures (laboratory evaluation). The aggregate gradations and air void contents for the test item mixtures were inconsistent and varied from the desired target values. This variation in mix properties introduced additional variability that affected the performance of the test items. Field compaction (level of compaction) also added to the variables of the test items. This variability added to the complexity of evaluating HMA mixtures and indicated that pavement performance (rutting potential) is affected by many factors including material properties, HMA production, and HMA placement and compaction.

Table 50. Rut Depth Measurements at Various Traffic Levels

Item number	Rut Depth (in.)						
	600 passes	1,200 passes	2,400 passes	4,800 passes	7,200 passes	9,600 passes	12,000 passes
1	0.21	0.22	0.26	0.27	0.29	0.29	0.29
2	0.19	0.24	0.30	0.41	0.54	0.54	0.54
3	0.29	0.33	0.44	0.47	0.47	0.53	0.53
4	0.20	0.24	0.26	0.40	0.81	0.88	0.94
5	0.17	0.22	0.28	0.40	0.48	0.65	0.69
6	0.32	0.38	0.58	0.65	0.71	0.71	0.71
7	0.26	0.30	0.35	0.63	0.69	0.73	0.73
8	0.25	0.31	0.50	0.75	0.81	1.02	1.02
9	0.14	0.17	0.22	0.33	0.58	0.58	0.60
10	0.17	0.21	0.27	0.40	0.54	0.58	0.58

Table 51. Rut Depth Measurements After 12,000 Passes

Item number	Rut depth (in.)
1	0.29
2	0.54
3	0.53
4	0.94
5	0.69
6	0.71
7	0.73
8	1.02
9	0.60
10	0.58

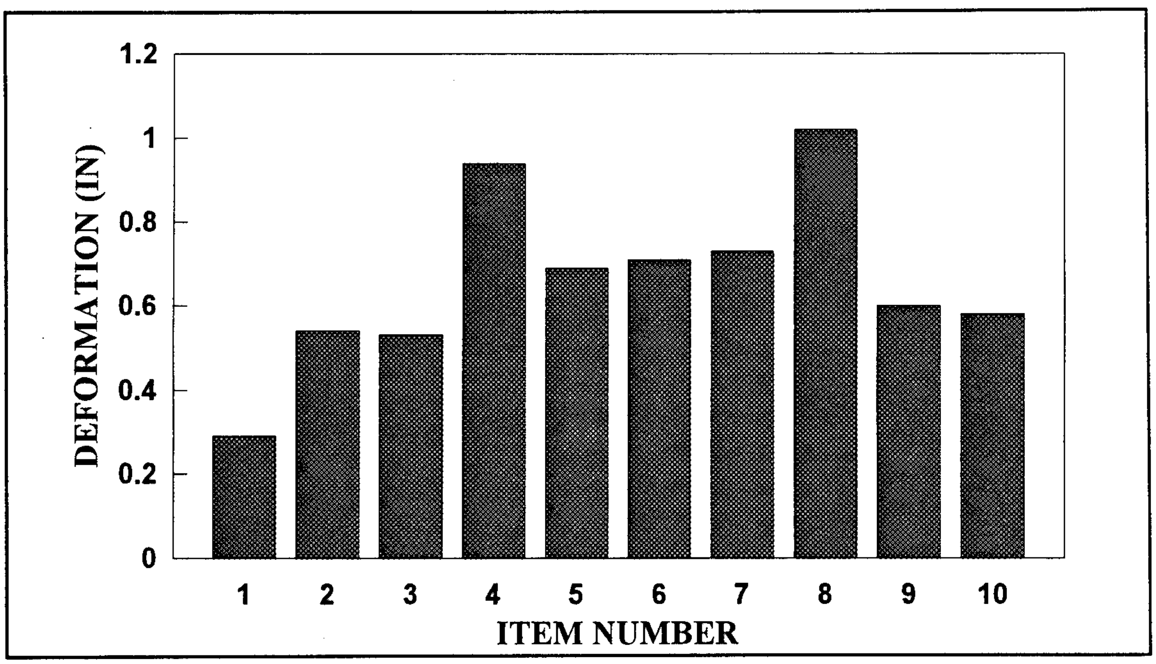


Figure 56. Rut Depth Values After 12,000 Passes of Aircraft Loads

The analysis of the test results from the field evaluation included determining the effect of aggregate gradation, percent crushed coarse aggregate, natural sand content, and asphalt modification on the rutting characteristics of HMA mixtures. This portion of the evaluation emphasized the trends and performance demonstrated by these different variable groups. The analysis also included correlating individual aggregate and HMA mixture properties with rut depth measurements. Since the test items were produced and constructed with many variables, the critical aggregate and HMA mixture properties that influenced the rutting characteristics are summarized and presented in Table 52.

Shape of Aggregate Gradation Curve

The effect of the shape of the aggregate gradation curve on the rutting characteristics of HMA mixtures was originally planned to be evaluated in test items 1, 3, 4, and 6. But, due to multiple aggregate properties and the inconsistency of the test items, the effect of gradation was not analyzed because of insufficient data.

Percentage of Crushed Coarse Aggregate

Based on the findings in the literature and results of the laboratory evaluation, the percentage of crushed coarse aggregate has a significant influence on rutting potential of HMA mixtures. This aggregate property was evaluated in Items 1, 8, and 9. The field performance of these test items indicated that the percentage of crushed coarse aggregate did affect the rutting characteristics of these HMA mixtures. The rut depth measurement approximately doubled (0.29 in. to 0.60 in.) when the percent crushed coarse aggregate was

Table 52. Critical Aggregate and HMA Mixture Properties of Test Items

Item	Asphalt binder type	Percent crushed coarse particles	Natural sand content	Percent air voids			Rut depth (in.)
				Lab compacted	After construction	After traffic	
1	AC-20	99	15	4.4	9.5	4.1	0.29
2	SBS modified AC-20	100	25	2.4	7.5	2.8	0.54
3	AC-20	98	5	4.6	9.9	2.6	0.53
4	AC-20	96	20	6.6	7.4	3.5	0.94
5	SBS modified AC-20	95	20	2.3	5.7	1.6	0.69
6	AC-20	95	40	7.2	9.4	6.5	0.71
7	SBS modified AC-20	92	40	5.2	7.8	4.9	0.73
8	SBS modified AC-20	11	0	3.5	6.3	3.7	1.02
9	AC-20	47	0	3.2	8.3	3.5	0.60
10	SBS modified AC-20	55	0	2.4	7.5	1.8	0.58

decreased from 99 percent to 47 percent. The overall trend was that rutting potential increased as the percentage of crushed coarse aggregate decreased. This trend is shown graphically in Figures 57 and 58.

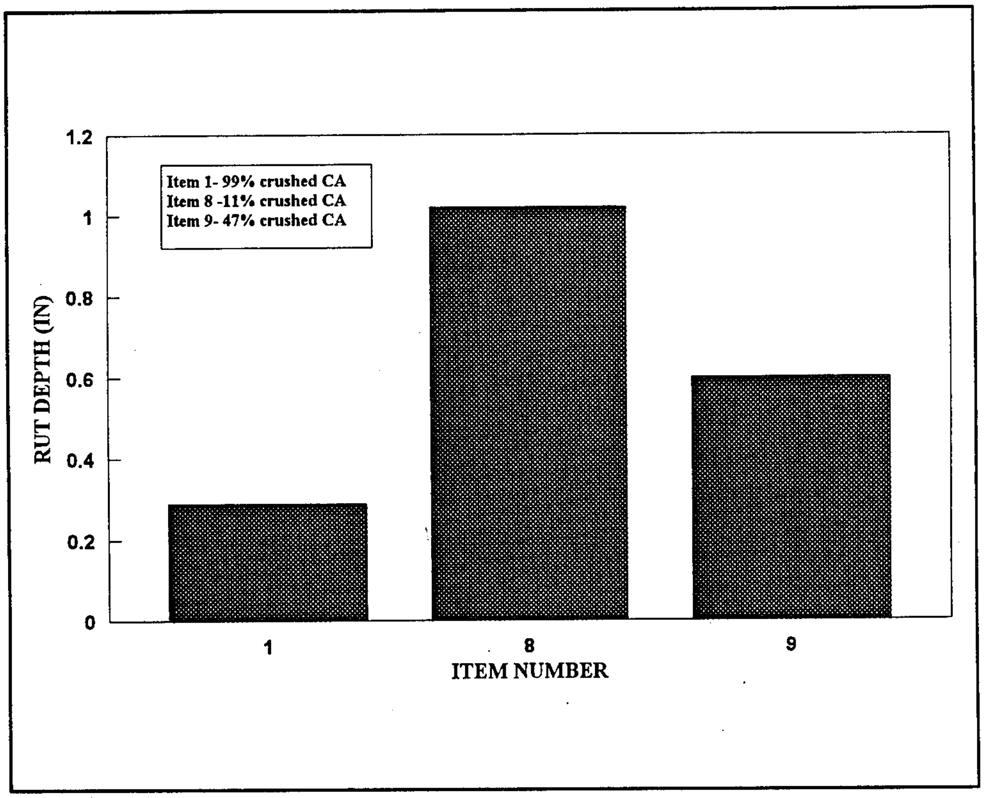


Figure 57. Effect of Percent Crushed Coarse Aggregate on Rut Depth Values

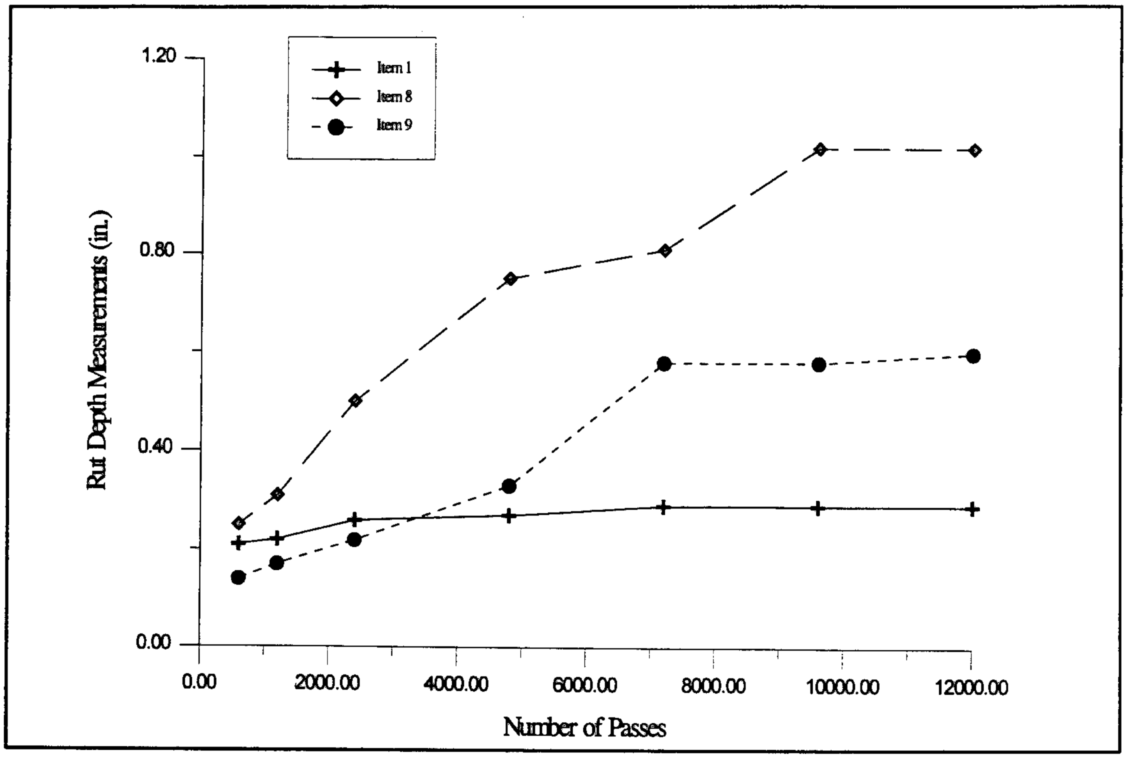


Figure 58. Cumulative Rut Depth for Percent Crushed Coarse Mixes

Amount of Natural Sand Material

The effect of the amount of natural sand material in an aggregate blend was evaluated in Items 1, 4, and 6. This evaluation combines the effects of particle shape and texture and fine aggregate gradation on the rutting characteristics of HMA mixtures. The performance of these test items indicated that the rutting potential increased when the amount of natural sand material was 20 percent or greater. The rut depth values indicated an increase in rutting potential when the natural sand content was greater than 15 percent. This increase in rutting potential is shown graphically in Figures 59 and 60.

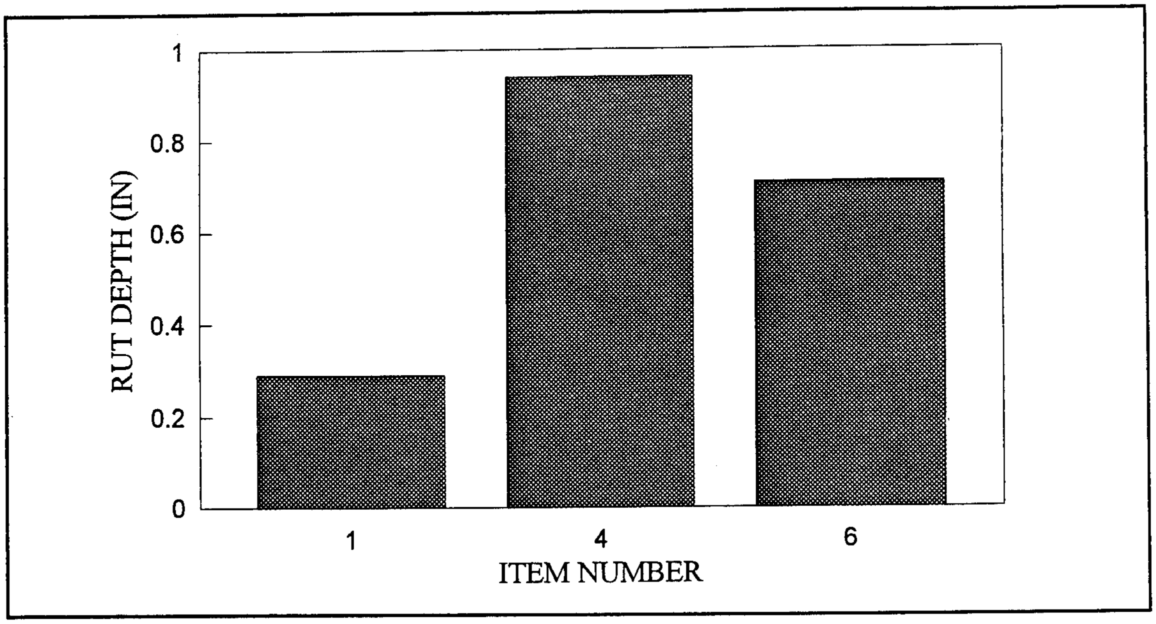


Figure 59. Effect of Natural Sand Content on Rut Depth Values

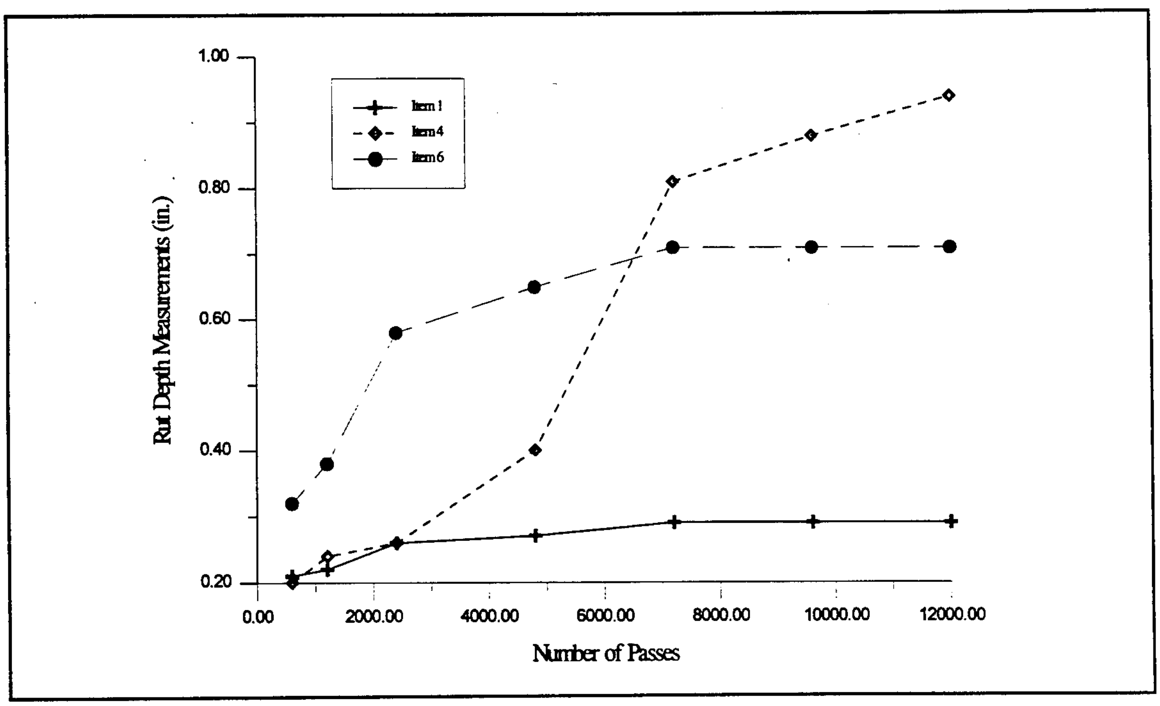


Figure 60. Cumulative Rut Depth for Natural Sand Mixes

Benefits of Asphalt Modification

The benefits of asphalt modification were evaluated for two conditions: (1) direct comparison of AC-20 and SBS-modified AC-20 mixtures with identical aggregate blend, and (2) comparison of mixtures with substandard aggregate blends produced with SBS-modified AC-20 to a control mix (Item 1). The direct comparison was conducted on three aggregate blends, 20 percent natural sand (Items 4 and 5), 40 percent natural sand (Items 6 and 7), and 50 percent crushed coarse aggregate (Items 9 and 10). The comparison of modified substandard aggregate blends to the control mix was conducted with Items 1, 2, 5, 7, 8, and 10.

The effect of asphalt modification on the test item HMA mixtures is shown in Figures 61 and 62. The findings of this analysis indicated that SBS modification only improved the aggregate blend with 20 percent natural sand (Item 5) and had no positive effect on the substandard aggregate blends. The addition of SBS modification did not improve the rutting characteristics of substandard aggregate HMA mixtures.

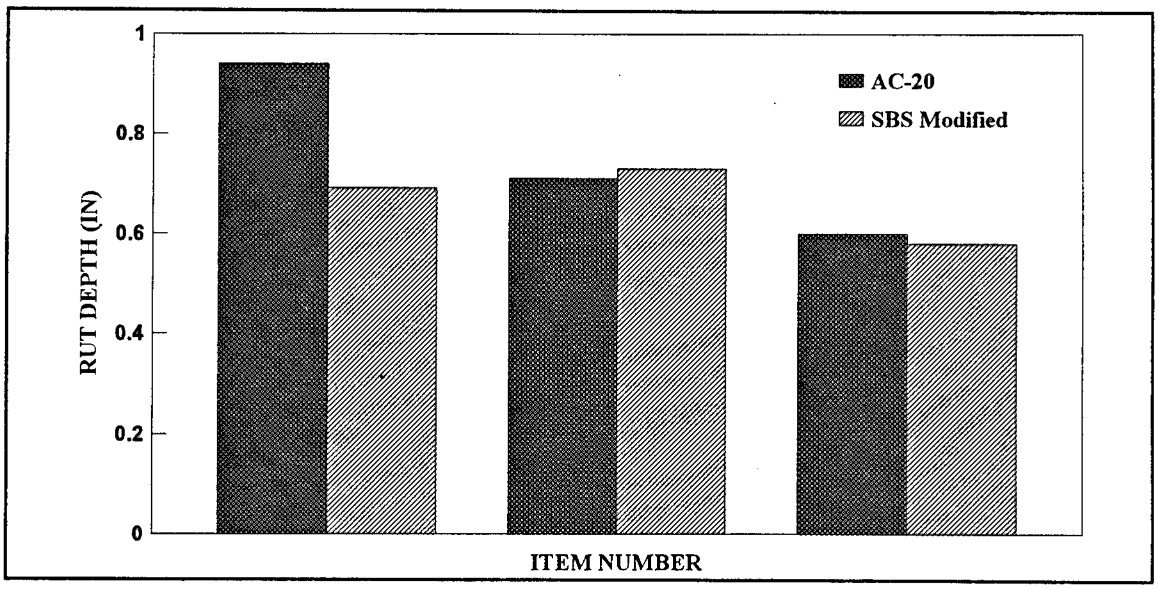


Figure 61. Effect of Asphalt Modification on Rut Depth Values

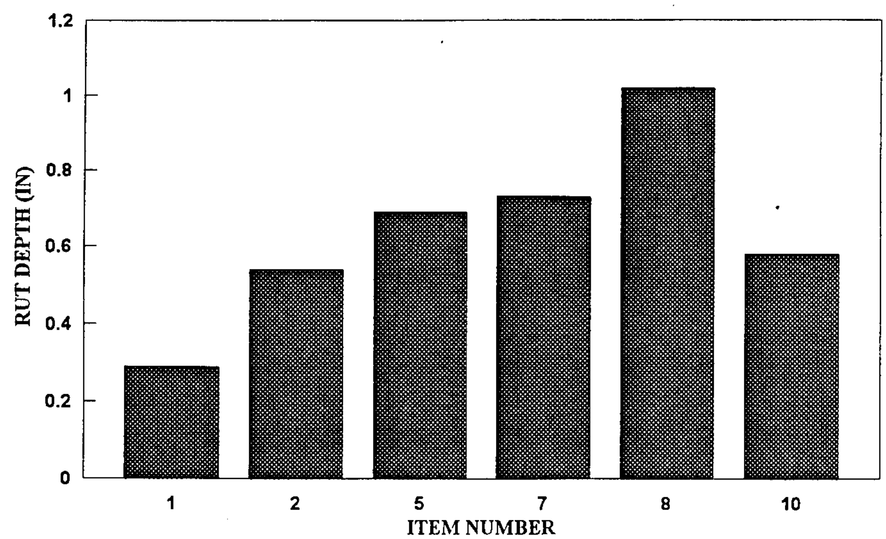


Figure 62. Effect of Asphalt Modification on Substandard Aggregate Blends

Correlation of Aggregate and HMA Mixture Properties with Permanent Deformation Values

One focus of the analysis procedure consisted of performing correlation analyses to determine if the independent variables were significantly correlated to the dependent variables rut depth and rutting rate. The independent variables were analyzed in four groups: (1) aggregate gradation, (2) aggregate characterization properties, (3) HMA mixture properties, and (4) confined repeated load deformation properties. The data were analyzed using SigmaStat statistical software package. (76) The coefficient of determination (R^2) was used to determine how strong the relationship was between the independent variables and the dependent variables. The R^2 value indicated the strength of the linear correlation. The R^2 values closer to 1, indicate a better relationship between independent and dependent variables.

The analysis of the aggregate gradation and aggregate characterization properties was conducted without Items 2, 5, and 10. These items were produced with HMA mixtures that had air voids measured on laboratory compacted specimen below 2.5 percent. The low air voids would influence the HMA performance and overshadow the effects of the aggregate properties. The values of these test items were included in the analysis of the HMA mixture properties.

Aggregate Gradation

The performance of HMA mixtures is greatly affected by the aggregate gradation because the gradation controls the void structure (matrix). Although the gradation is important to the performance of HMA, the effect of the gradation is often difficult to quantify. For this study, the percent passing each sieve size was analyzed to determine the effect of aggregate gradation on rut depth. A summary of coefficients of determination for aggregate gradation is presented in Table 53. The R^2 values indicated that only the 1/2 in. and 3/8 in. sieves had any statistically significant relationships with rutting. The R^2 values for the 1/2 in. and 3/8 in. sieves with rut depth were 0.448 and 0.812. The results of the linear regression analysis for the 3/8 in. sieve correlation are shown in Figure 63.

Table 53. Summary of Coefficients of Determinations for Aggregate Gradation

Parameter	n	Rut depth R^2
Percent passing 1/2 in. sieve	7	0.448
Percent passing 3/8 in. sieve	7	0.812
Percent passing No. 4 sieve	7	0.194
Percent passing No. 8 sieve	7	0.039
Percent passing No. 16 sieve	7	0.050
Percent passing No. 30 sieve	7	0.017
Percent passing No. 50 sieve	7	0.042
Percent passing No. 100 sieve	7	0.046
Percent passing No. 200 sieve	7	0.044

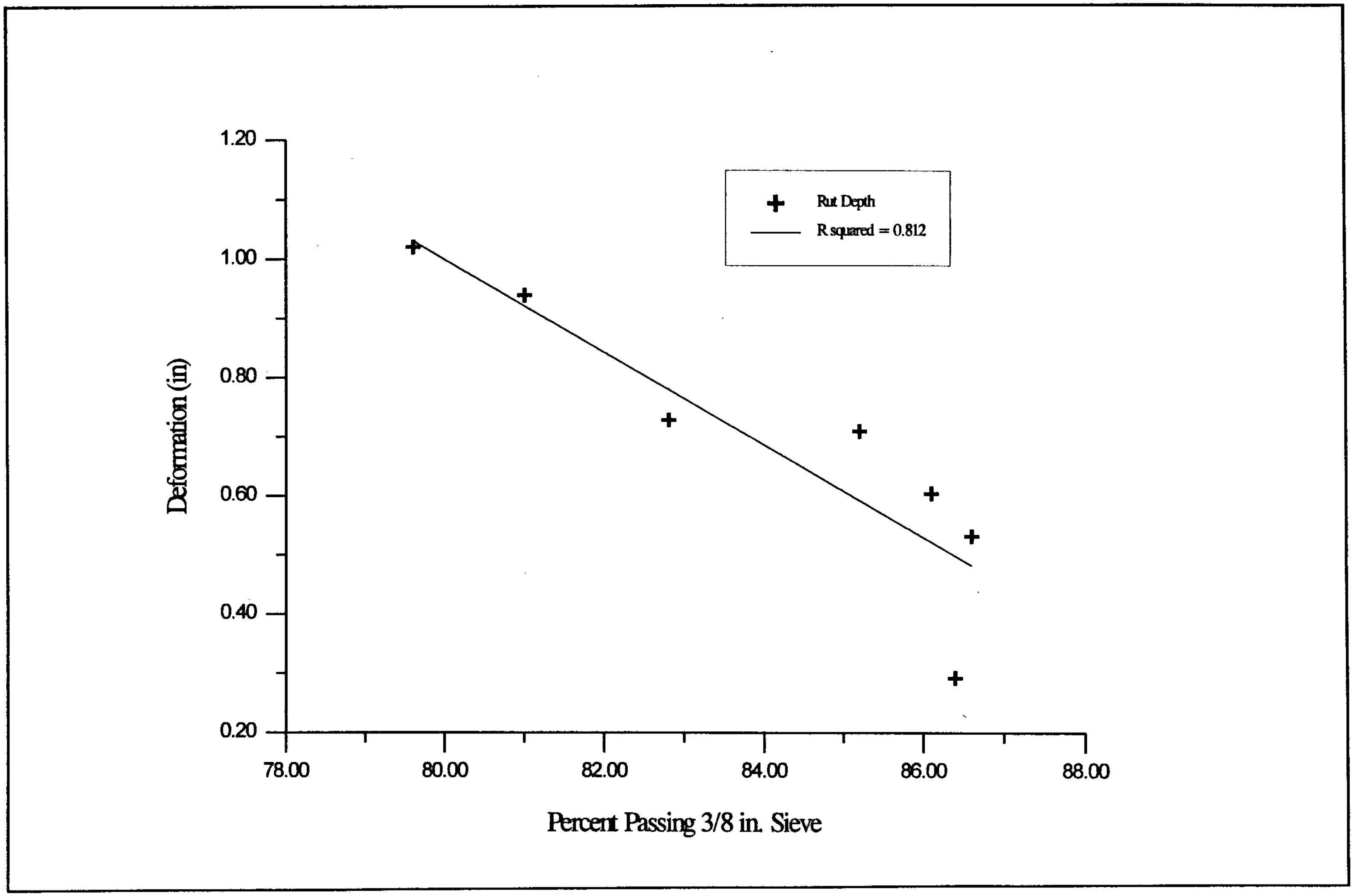


Figure 63. Deformation Measurements versus Percent Passing 3/8 in. Sieve

Aggregate Characterization Properties

As previously shown in the laboratory evaluation (Chapter 5), aggregate properties (shape and texture) have a significant affect on the rutting potential of HMA mixtures. One of the objectives of this study was to characterize and quantify aggregate properties and to determine the influence of these properties on the performance of HMA mixtures. Several aggregate characterization tests were conducted on extracted aggregates from test item mixtures and correlated with rut depth and rutting rate. A summary of R^2 values for aggregate characterization properties is presented in Table 54. The percent crushed particles (composite blend and coarse aggregate fraction) produced the only strong individual correlations with rut depth. The R^2 value for percent crushed coarse particles was 0.249 for rut depth values. This correlation is shown in Figure 64.

HMA Mixture Properties

Because rutting is a very complicated process, several types of HMA mixture properties (i.e., voids, strength, deformation) were determined to evaluate HMA properties with rutting. Traditional volumetric and Marshall properties along with gyratory compaction and direct shear properties were used to analyze the test item HMA mixtures with rut depth and rutting rate. A summary of R^2 values for HMA mixture properties is presented in Table 55. The R^2 values indicated that the stability/flow ratio (77) was the only HMA mixture property that had a strong relationship with rut depth. This correlation had a R^2 value of 0.528 for rut depth. The results of linear regression analysis for the stability/flow ratio is shown in Figure 65.

Table 54. Summary of Coefficients of Determination for Aggregate Characterization Properties

Parameter	n	Rut depth R^2
Percent crushed particles-composite	7	0.177
Percent crushed particles-coarse	7	0.249
Percent crushed particles-fine	7	0.002
Natural sand content	7	0.001
Modified NAA	7	0.078
ASTM C-29 shovel	7	0.124
NAA Method A	7	0.109
NAA Method C	7	0.097
Direct shear	7	0.036

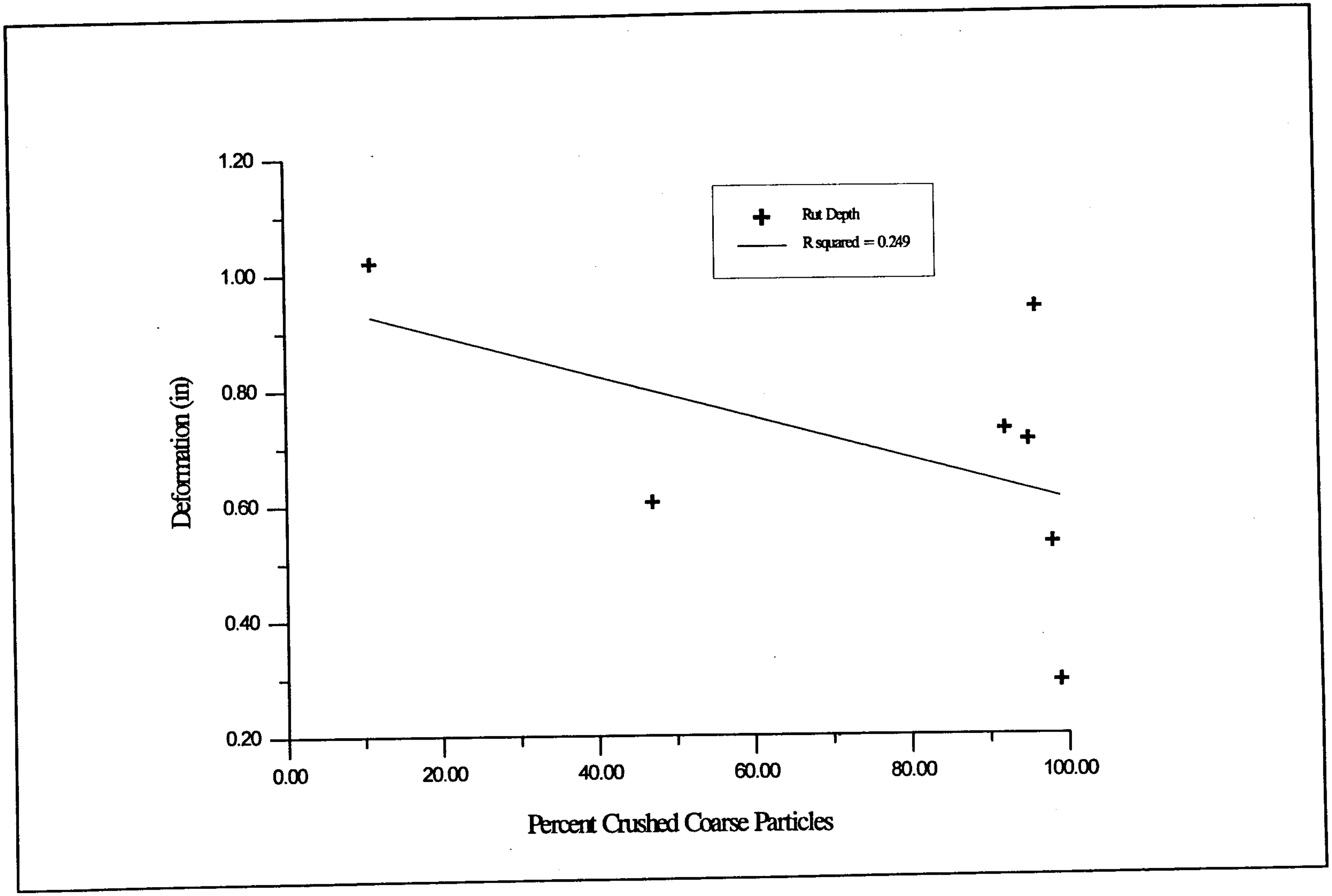


Figure 64. Deformation Measurements versus Percent Crushed Coarse Particles

Table 55. Summary of Coefficients of Determination for HMA Mixture Properties

Parameter	n	Rut depth R^2
Air voids - lab compacted	10	0.070
Voids in mineral aggregate	10	0.219
Voids filled	10	0.029
Stability	10	0.160
Flow	10	0.086
Stability/flow	10	0.528
GEPI	10	0.204
Gyratory shear strength	10	0.148
Angle of internal friction	10	0.001
Direct shear strength	10	0.145
Inplace air voids after construction	10	0.340
Inplace air voids after traffic	10	0.019
Permanent strain lab compacted	10	0.060
Creep modulus lab compacted	10	0.073
Slope lab compacted	10	0.069
Permanent strain field compacted	10	0.043
Creep modulus field compacted	10	0.014
Slope field compacted	10	0.070

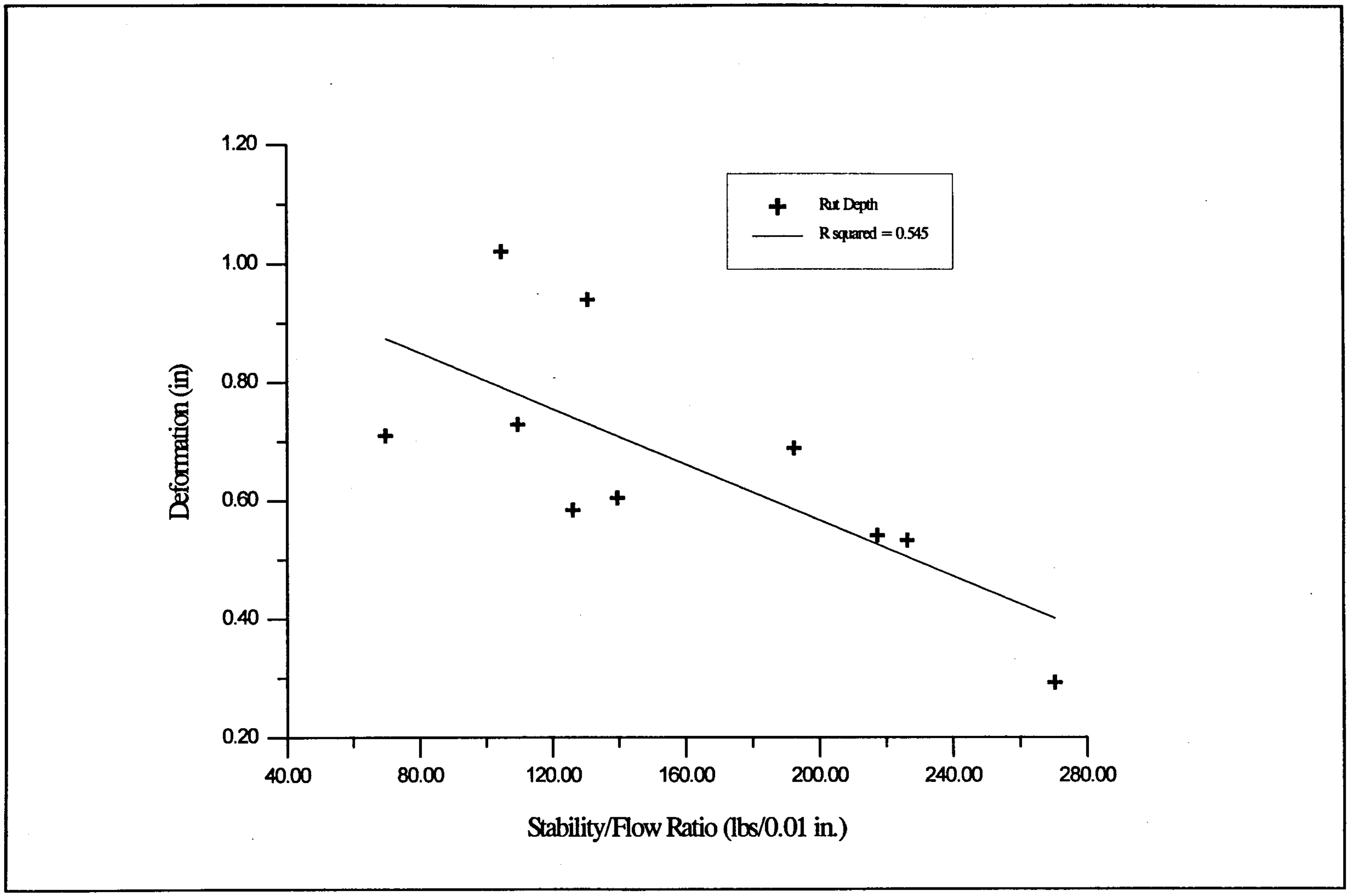


Figure 65. Deformation Measurements versus Marshall Stability/Flow Ratio

Confined Repeated Load Deformation Properties

One of the primary objectives of this research study was to validate the confined repeated load deformation test with field cores and rutting after traffic. This test method had been reported to be one of the best procedures to evaluate permanent deformation since this type test more closely simulates the in situ pavement conditions under traffic. (44,70,71) The confined repeated load deformation test was conducted on plant-mixed HMA material compacted in the laboratory and field compacted with conventional asphalt rollers (vibratory and rubber-tired). The correlations indicated weak relationships between the confined repeated load deformation test results and actual rutting in the field. The field compacted specimen produced better correlations than the lab compacted specimen. These results are logical because the laboratory compacted specimen are compacted to approximately 100 percent lab density while the inplace pavement is compacted to approximately 95 percent lab density.

In order to simulate field conditions, the confined repeated load deformation test should be conducted on laboratory samples that are compacted to densities that approximate field conditions.

Summary

The results of the statistical analysis indicated that few aggregate and HMA mixture properties have a significant relationship with pavement rutting. Although the correlations were weak, most aggregate and HMA properties appeared to have definite trends. It was evident from the data that rutting is influenced by multiple factors (i.e., percent crushed particles, gradation, stiffness of HMA, and inplace voids) and cannot be predicted with individual aggregate and HMA mixture properties. Surprisingly, the Marshall stability/flow ratio had the single best individual correlation with rutting in HMA pavements. A major factor affecting the analysis was varying laboratory air voids for the test items.

CHAPTER VII DEVELOPMENT OF RUTTING MODELS

Based on the findings and the results presented in Chapter VI, there was no single aggregate or HMA mixture property that has a strong individual relationship with permanent deformation. These results proved that rutting in HMA pavements is a complex process. This chapter presents and discusses the development of rutting models using forward stepwise multiple linear regression analysis. These analyses were conducted using the SigmaStat statistical software package. (76)

The multiple linear regression analyses were conducted using a selected database from the four independent variable groups. The individual parameters selected from each group are listed in Table 56. These parameters encompassed the range of the aggregate gradation properties, aggregate characterization properties, HMA mixture properties, and the confined repeated load deformation test properties. A model to predict rut depth was developed for aggregate properties, HMA mixture properties, and an overall model including all independent variables. The models developed for rut depth are based on limited data and are intended to illustrate trends, not to predict rut depths in HMA pavements.

Table 56. Selected Database for Rut Depth Models

Independent variable groups	Parameters
Aggregate gradation	1/2 in. sieve
	3/8 in. sieve
	No. 4 sieve
	No. 8 sieve
	No. 30 sieve
Aggregate characterization properties	Percent crushed particles - composite
	Percent crushed particles - coarse
	Natural sand content
	NAA Method A
	Modified NAA
	ASTM C 29 (shovel)
HMA mixture properties	VTM
	VMA
	VF
	Stability
	Flow
	Stability/flow ratio
	GEPI
	Gyratory shear strength
	Inplace air voids after construction
	Inplace air voids after traffic
Confined repeated load deformation test properties	Permanent strain - field compacted
	Creep modulus - field compacted
	Slope - field compacted

AGGREGATE PROPERTIES

The linear regression model produced by forward stepwise procedure for aggregate properties included the variable percent passing the 3/8 in. sieve. This correlation produced a R^2 value of 0.812 and is shown graphically in Figure 66. The trend of this model indicated that rut depth decreased as the percentage of material passing the 3/8 in. sieve increased. This trend agrees with the findings of the laboratory evaluation, but is contrary to other research findings that show larger percentages of coarse aggregate produce less rutting. The equation of this multiple linear regression correlation has the following form:

$$RD = 7.27 - 0.078\ (3/8\ \text{in.})$$

where:
RD = Predicted rut depth (in.)
3/8 in. = Percent passing 3/8 in. sieve (%)

HMA MIXTURE PROPERTIES

The multiple linear regression model developed for HMA mixture properties using the forward stepwise procedure included the variables Marshall stability/flow ratio and inplace air voids after construction. This correlation produced a R^2 value of 0.702 and is shown graphically in Figure 67. The trend of this model indicated that rut depth decreased with an increase in the Marshall stability/flow ratio and inplace air voids. These trends were expected, and agree with other research findings that indicated rutting decreased with increased mixture stiffness and air voids. The equation of this correlation has the following form:

$$RD = 1.50 - 0.0020\ (SFR) - 0.0654\ (IAV_{AC})$$

where:
RD = Predicted rut depth (in.)
SFR = Marshall stability/flow ratio (lb./0.01 in.)
IAV_{AC} = Inplace air voids after construction

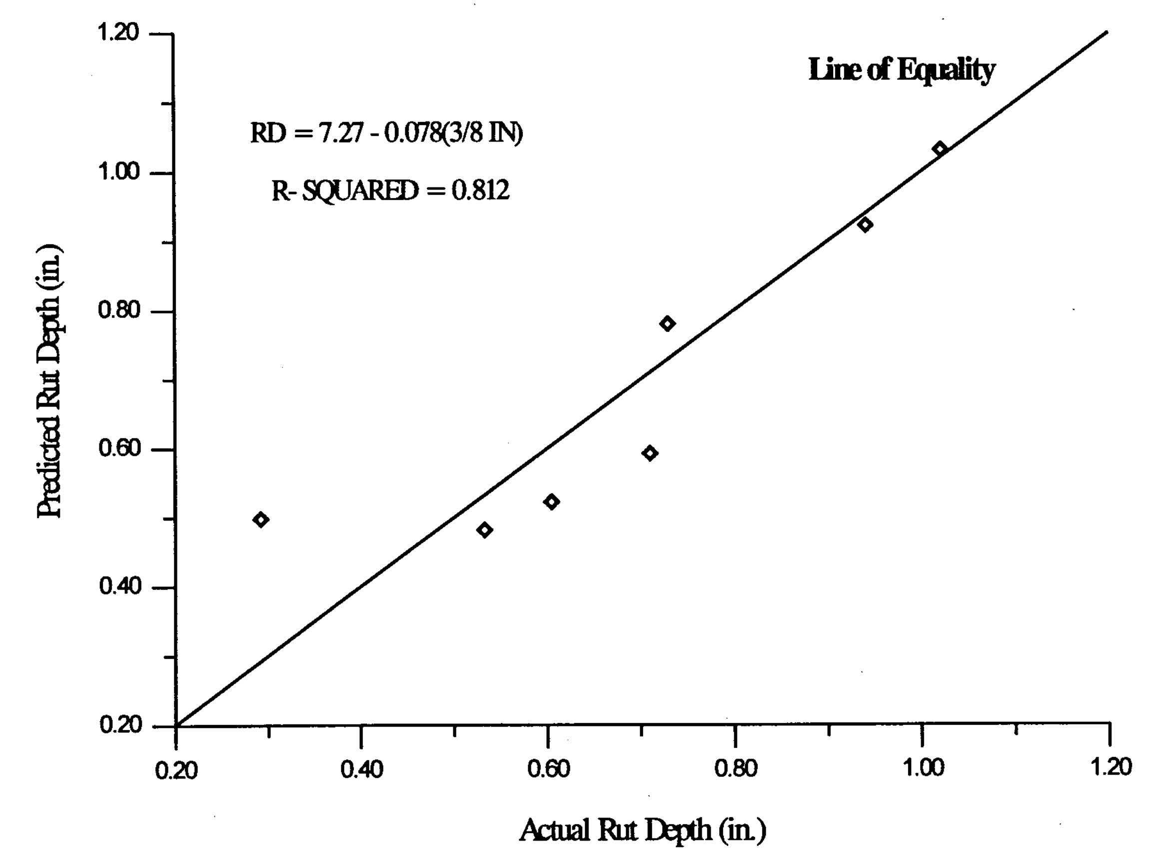


Figure 66. Predicted Rut Depth versus Actual Rut Depth for Aggregate Properties

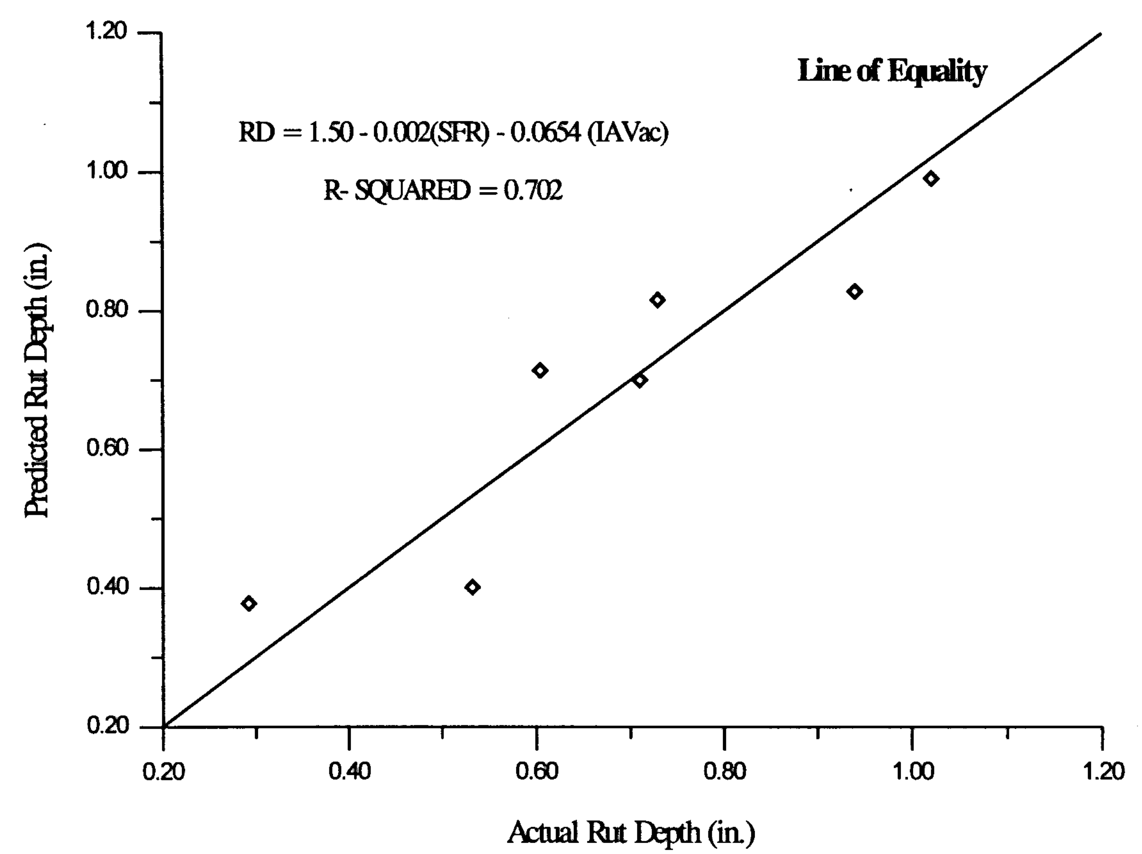


Figure 67. Predicted Rut Depth versus Actual Rut Depth for HMA Mixture Properties

OVERALL MODEL

The overall multiple linear regression model that was developed using the forward stepwise procedure for all the selected independent variables included an aggregate gradation property (percent passing 3/8 in. sieve) and a HMA mixture property (stability/flow ratio). This model shows that rutting in HMA pavements is influenced by both aggregate and mixture properties. This correlation produced a R^2 value of 0.920 and is shown graphically in Figure 68. The equation of this correlation has the following form:

$$RD = 5.87 - 0.059\ (3/8\ in.) - 0.0014\ (SFR)$$

where:

RD	=	Predicted rut depth (in.)
3/8 in.	=	Percent passing 3/8 in. sieve (%)
SFR	=	Marshall stability/flow ratio (lb/0.01 in.)

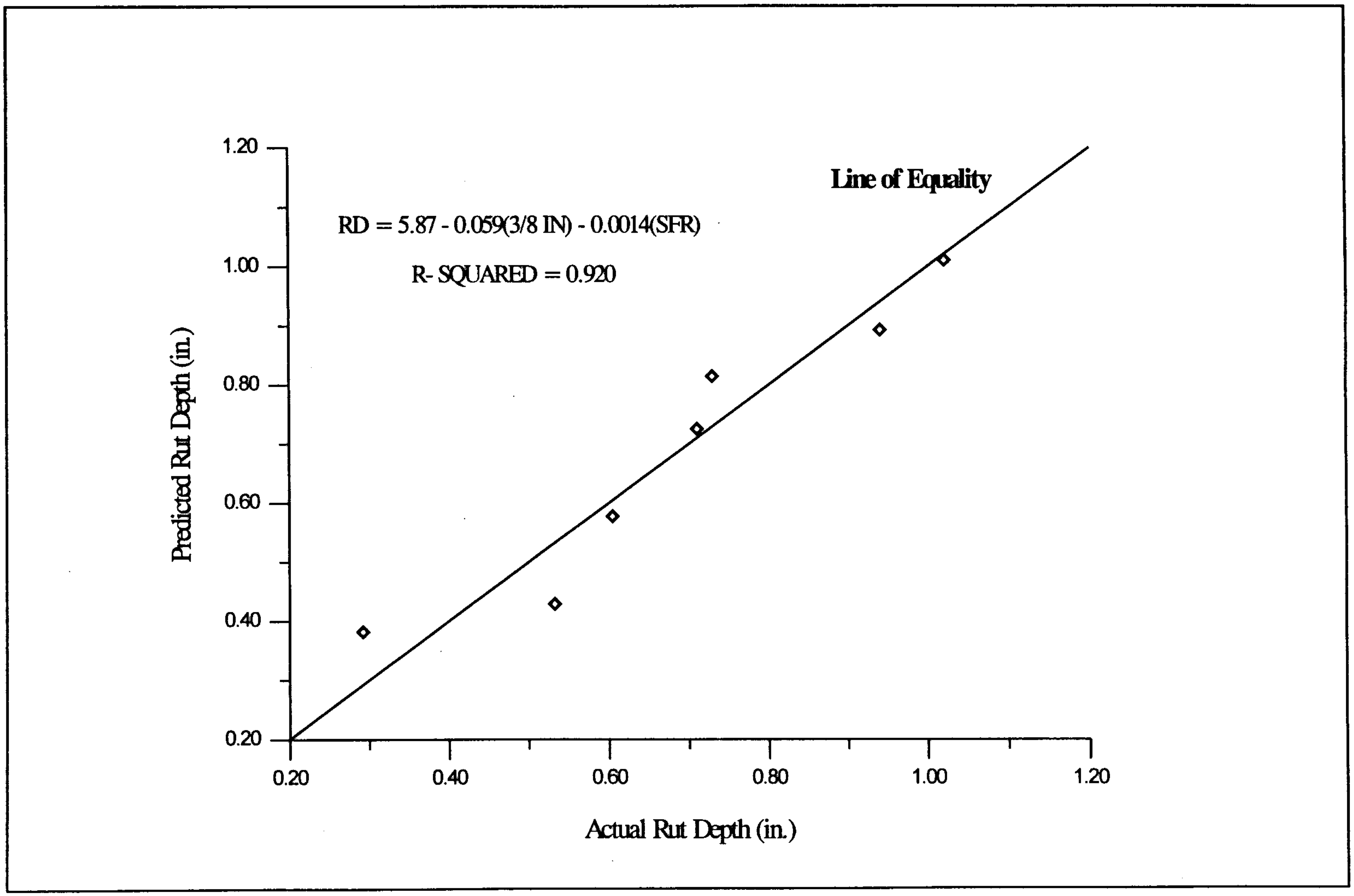


Figure 68. Predicted Rut Depth versus Actual Rut Depth - Overall Model

CHAPTER VIII CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The objective of this research study was to evaluate the influence of aggregate gradation and particle shape and texture on permanent deformation characteristics of HMA and modified HMA mixtures. The primary focus of this evaluation was to characterize and quantify aggregate properties with performance-related tests and to develop relationships between physical properties of aggregates and the rutting potential of HMA pavements. The following conclusions were derived from the analyses of the laboratory and field evaluations.

Laboratory Evaluation

1. The Particle Index test characterized the shape and texture of the aggregate blends very effectively. The Particle Index test results produced strong relationships with percent crushed particles (composite, coarse, fine) and the natural sand content. The short-cut versions of this test method, major sieve and 2nd major sieve fractions, did not produce strong correlations when compared to the composite Particle Index values.

2. The modified NAA particle shape and texture test produced good correlation with percent crushed coarse aggregate. Method 1 (as-prepared) produced a R^2 value of 0.891.

3. Both the rodding and shoveling procedures of ASTM C 29 produced excellent correlations with percent crushed coarse particles. The rodding procedure produced void contents approximately 4 percent lower than the shoveling procedure.

4. Method A of the NAA particle shape and texture test produced stronger relationships with percent crushed fine particles and the natural sand content than did Method C.

5. The direct shear test method for fine aggregates did not correlate well with percent crushed fine particles and the natural sand content in the aggregate blend.

6. The GEPI values produced strong correlations with the composite aggregate blend and the coarse aggregate fraction characterization test results. These strong correlations indicated that the GEPI value did measure the aggregate quality (shape and texture) in an asphalt-aggregate mixture.

7. Based on strong correlations and simple test procedures, the best alternatives for specification requirements to characterize aggregate particle shape and texture instead of percent crushed particles are modified NAA particle shape and texture test for coarse aggregate fraction and the NAA particle shape and texture test for fine aggregate fraction. The Particle Index test and the GEPI value could be used to specify the aggregate characterization properties for the composite aggregate blend.

8. The shape of the aggregate gradation curve had a significant effect on laboratory permanent deformation properties. The asphalt-aggregate mixtures that produced the better permanent deformation characteristics were with aggregate gradations finer than the maximum density line (Mixes C and D) and two poorly-graded gradations (Mixes F and G). Each of these mixtures produced better rutting characteristics than the mixture produced with an aggregate gradation falling on the center of the FAA gradation band. The two

poorly-graded gradations both have large percentages of material retained on the No. 4 sieve which can produce stone on stone contact (similar to SMA mixtures).

9. The percentage of crushed coarse particles had a significant effect on laboratory permanent deformation properties. As the percentage of crushed coarse particles decreased, the rutting potential of the HMA mixtures increased.

10. An increase in the natural sand content had an adverse effect on the laboratory permanent deformation properties. HMA mixtures with greater than 10 percent by weight produced results that indicated increased rutting potential.

11. The Marshall stability test, direct shear strength test, gyratory compaction properties, and the confined repeated load deformation test were all sensitive to aggregate property changes and could be used to evaluate the effects of aggregate properties on HMA mixtures.

12. The modified asphalt binders (SBS modified AC-20, and LDPE modified AC-20) did improve some of the laboratory HMA mixtures to be equivalent or better than the control AC-20 HMA mixtures. Each modified asphalt binder improved the Marshall stability values, the GEPI values, the indirect tensile strength values, and the direct shear strength values with varying success. The SBS modified AC-20 binder had the greatest positive effect on mixture strength.

13. Each of the modified asphalt binders reduced the GEPI values which had the same effect as improving the quality of the aggregates shape and texture.

14. Asphalt modification had little effect on rutting characteristics of the limestone mixtures (Mix A, C, and E), but did produce significant improvements in the gravel mixtures (Mix I, O, M, Q, and R).

Field Evaluation

15. The percentage of crushed coarse aggregate had a significant effect on the rutting potential of the field test items. As the percentage of crushed coarse aggregate decreased, the potential for rutting increased.

16. SBS modification improved the rutting characteristics of the aggregate blend with 20 percent natural sand, but had no positive effect on the substandard aggregate blends.

17. The Marshall stability/flow ratio produced the strongest correlation with rutting of all HMA mixture properties. The R^2 values for this HMA mixture property with rut depth was 0.528.

18. The strongest model to predict rut depths in HMA pavements was a function of an aggregate property (percent passing 3/8 in. sieve) and a HMA mixture property (stability/flow ratio). This multiple linear regression correlation produced a strong relationship that produced a R^2 value of 0.920.

RECOMMENDATIONS

Based on the conclusions derived from the results of this research study, the following recommendations were made:

1. Current aggregate specifications could be improved by implementing performance related aggregate properties determined by the Particle Index test and the NAA and modified NAA particle shape and texture tests. Initial preliminary guidance and criteria could be implemented based on values determined in this study, but final criteria should be established based on additional research involving a variety of aggregate types and sources.

2. Additional research is needed to fully evaluate the poorly-graded mixtures and the potential of large aggregate mixtures and SMA mixtures.

3. Modified asphalt binders did improve the rutting characteristics of the HMA mixtures in the laboratory. Further research is needed to evaluate new and different asphalt modification techniques and to establish criteria for selecting the modifier type and dosage rate.

4. Further research is needed on the confined repeated load deformation test to evaluate various states of stress, time and rate of loading, compaction level, and specimen size. These test conditions should be validated with additional field cores and rut depths.

5. Further evaluation should be considered for the direct shear device and the Gyratory Testing Machine for determining HMA mixture shear strengths. Additional field data should be analyzed to determine relationship between shear strength and pavement rutting.

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APPENDIX A: LABSTOCK AGGREGATE GRADATIONS AND SPECIFIC GRAVITIES

Table A1. Crushed Limestone Labstock Aggregate Gradations and Specific Gravities

Sieve size	Size Fraction - Percent Passing								
	3/4 in.- 1/2 in.	1/2 in.- 3/8 in.	3/8 in.- No. 4	No. 4- No. 8	No. 8- No. 16	No. 16- No. 30	No. 30- No. 50	No. 50- No. 100	No. 100- No. 200
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	16.5	99.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in.	0.4	23.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. 4	0.3	0.3	15.2	99.8	100.0	100.0	100.0	100.0	100.0
No. 8		0.3	1.2	51.2	99.8	100.0	100.0	100.0	100.0
No. 16			1.2	2.9	22.1	99.9	100.0	100.0	100.0
No. 30			1.2	2.6	8.1	45.7	99.3	99.9	100.0
No. 50			1.2	2.5	7.6	13.1	41.9	98.0	100.0
No. 100			1.1	2.4	6.8	8.2	8.3	40.5	97.5
No. 200			1.0	2.2	5.8	6.8	6.9	14.6	70.9
Apparent	2.833	2.819	2.873	2.859	2.855	2.851	2.850	2.827	2.838
Bulk ssd	2.818	2.805	2.851	2.856	2.852	2.847	2.843	2.820	2.838
Bulk	2.809	2.797	2.839	2.855	2.851	2.844	2.840	2.816	2.838
Absorption	0.3	0.3	0.4	0.1	0.1	0.1	0.1	0.1	0

Table A2. Crusted Gravel Labstock Aggregate Gradations and Specific Gravities

Sieve size	Size Fraction - Percent Passing								
	3/4 in.- 1/2 in.	1/2 in.- 3/8 in.	3/8 in.- No. 4	No. 4- No. 8	No. 8- No. 16	No. 16- No. 30	No. 30- No. 50	No. 50- No. 100	No. 100- No. 200
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	37.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in.	0.7	36.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. 4	0.7	2.4	11.4	99.5	100.0	100.0	100.0	100.0	100.0
No. 8		2.4	1.3	15.0	99.8	100.0	100.0	100.0	100.0
No. 16		2.4	1.3	2.9	15.4	100.0	100.0	100.0	100.0
No. 30			1.2	2.8	5.3	22.2	99.8	100.0	100.0
No. 50			1.1	2.6	4.7	4.5	44.2	95.6	99.7
No. 100			1.0	2.2	4.1	3.6	11.8	70.2	94.2
No. 200			0.8	1.8	3.6	3.1	6.9	9.4	43.3
Apparent	2.606	2.606	2.623	2.609	2.618	2.635	2.605	2.565	2.698
Bulk ssd	2.565	2.559	2.549	2.541	2.541	2.575	2.556	2.510	2.698
Bulk	2.540	2.530	2.503	2.499	2.493	2.538	2.525	2.475	2.698
Absorption	1.0	1.2	1.8	1.7	1.9	1.5	1.2	1.4	0.0

Table A3. Uncrushed Gravel Labstock Aggregate Gradations and Specific Gravities

Sieve size	Size Fraction - Percent Passing							
	3/4 in.- 1/2 in.	1/2 in.- 3/8 in.	3/8 in.- No. 4	No. 4- No. 8	No. 8- No. 16	No. 30- No. 50	No. 50- No. 100	No. 100- No. 200
3/4 in.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in.	9.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in.	1.4	16.8	100.0	100.0	100.0	100.0	100.0	100.0
No. 4	1.3	1.4	6.8	99.4	100.0	100.0	100.0	100.0
No. 8	1.3	1.3	3.2	12.1	99.9	100.0	100.0	100.0
No. 16		1.3	3.2	4.6	36.5	100.0	100.0	100.0
No. 30			3.0	4.3	29.5	99.5	100.0	100.0
No. 50			1.8	2.4	12.2	28.6	95.5	99.1
No. 100			1.1	1.5	6.5	4.9	29.3	89.5
No. 200			0.9	1.2	5.7	3.9	14.1	32.6
Apparent	2.576	2.583	2.609	2.611	2.589	2.622	2.571	2.649
Bulk ssd	2.522	2.517	2.528	2.564	2.548	2.595	2.540	2.649
Bulk	2.488	2.476	2.477	2.535	2.522	2.578	2.520	2.649
Absorption	1.4	1.7	2.0	1.2	1.0	0.6	0.8	0.0

Table A4. Natural Sands and Limestone Filler Labstock Aggregate Gradations and Specific Gravities

Sieve size	Percent Passing		
	Limestone filler	Fine sand	Coarse sand
3/4 in.	100.0	100.0	100.0
1/2 in.	100.0	100.0	100.0
3/8 in.	100.0	100.0	99.7
No. 4	100.0	100.0	97.1
No. 8	100.0	100.0	92.0
No. 16	100.0	99.9	88.2
No. 30	100.0	99.5	74.7
No. 50	100.0	98.3	10.8
No. 100	85.8	68.0	1.4
No. 200	64.3	8.0	0.8
Apparent	2.857	2.645	2.649
Bulk ssd	2.857	2.606	2.648
Bulk	2.857	2.583	2.648
Absorption	0.0	0.9	0.0

Table A5. Stockpile Materials for Test Section HMA Mixtures

	Percent Passing						
Sieve size	Crushed limestone #458	Crushed limestone #56	Crushed limestone screenings	Crushed gravel screenings	Unrushed coarse gravel	Concrete sand	Mason sand
1 in.	100	100	100	100	100	100	100
3/4 in.	100	100	100	100	73.9	100	100
1/2 in.	54.6	98.5	100	99.6	37.5	98.7	100
3/8 in.	31.3	80.1	100	98.1	17.9	97.9	100
No. 4	6.9	29.7	96.3	90.0	0.5	92.6	100
No. 8	2.3	6.3	59.3	64.2	0.5	81.9	99.9
No. 16	1.4	2.2	34.6	38.0	0.5	75.5	98.6
No. 30	1.0	1.2	27.1	23.9	0.5	63.6	87.8
No. 50	0.8	0.8	21.8	10.8	0.4	15.4	18.0
No. 100	0.5	0.6	17.9	6.8	0.3	2.9	2.1
No. 200	0.5	0.5	15.3	5.3	0.3	1.7	1.1
Apparent	2.764	2.750	2.688	2.641	2.597	2.634	2.648
Bulk ssd	2.752	2.736	2.676	2.560	2.564	2.619	2.638
Bulk	2.745	2.729	2.671	2.512	2.544	2.614	2.631
Absorption	0.3	0.3	0.2	1.9	0.8	0.3	0.3

APPENDIX B: CONFINED REPEATED LOAD DEFORMATION TEST RESULTS

Table B1. Confined Repeated Load Deformation Test Results for AC-20 Mixtures

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
A	2.440	4.0	0.0228	0.0228	8772	0.098
	2.449	4.0	0.0190	0.0190	10526	0.124
	2.449	3.9	0.0216	0.0216	9259	0.104
Avg	2.446	4.0	0.0211	0.0211	9479	0.109
Std	0.005	0.1	0.0019	0.0019	905	0.014
B	2.542	3.7	0.0312	0.0312	6410	0.230
	2.525	3.7	0.0212	0.0212	9434	0.159
	2.571	4.0	0.0329	0.0326	6079	0.246
Avg	2.546	3.8	0.0284	0.0283	7042	0.212
Std	0.023	0.2	0.0063	0.0062	1849	0.046
C	2.476	4.2	0.0250	0.0249	8000	0.091
	2.474	3.7	0.0205	0.0203	9756	0.074
	2.486	3.7	0.0162	0.0162	12346	0.115
Avg	2.479	3.9	0.0206	0.0205	9709	0.093
Std	0.006	0.3	0.0044	0.0044	2186	0.021

(Sheet 1 of 6)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
D	2.487	4.0	0.0201	0.0188	9950	0.081
	2.479	4.0	0.0187	0.0187	10695	0.091
	2.468	3.6	0.0227	0.0226	8811	0.083
Avg	2.478	3.9	0.0205	0.0200	9756	0.085
Std	0.010	0.2	0.0020	0.0022	949	0.005
E	2.468	4.0	0.0317	0.0316	6309	0.166
	2.457	4.5	0.0217	0.0216	9212	0.139
	2.472	4.2	0.0261	0.0260	7663	0.219
	2.475	4.4	0.0284	0.0270	7042	0.161
Avg	2.468	4.3	0.0270	0.0266	7407	0.171
Std	0.008	0.2	0.0042	0.0041	1235	0.034
F	2.483	3.8	0.0122	0.0120	16393	0.141
	2.468	3.5	0.0153	0.0149	13072	0.114
	2.474	3.8	0.0170	0.0168	11765	0.109
Avg	2.475	3.7	0.0148	0.0146	13514	0.121
Std	0.008	0.2	0.0024	0.0024	2386	0.017

(Sheet 2 of 6)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
G	2.473	4.3	0.0147	0.0146	13605	0.070
	2.468	4.4	0.0163	0.0156	12270	0.110
	2.478	4.4	0.0156	0.0156	12821	0.117
	2.472	4.3	0.0139	0.0123	14388	0.121
Avg	2.473	4.4	0.0151	0.0145	13245	0.105
Std	0.016	0.3	0.0010	0.0012	924	0.033
H	2.461	4.4	0.0236	0.0235	8475	0.087
	2.493	3.9	0.0221	0.0217	9050	0.151
	2.479	4.1	0.0239	0.0239	8368	0.106
Avg	2.478	4.1	0.0232	0.0230	8620	0.115
Std	0.016	0.3	0.0010	0.0012	367	0.033
I	2.732	4.3	0.0302	0.0300	6623	0.256
	2.718	4.5	0.0343	0.0343	5831	0.176
	2.729	4.4	0.0342	0.0342	5848	0.254
	2.767	4.0	0.0422	0.0422	4739	0.285
Avg	2.737	4.3	0.0352	0.0352	5682	0.243
Std	0.021	0.2	0.0050	0.0051	775	0.047

(Sheet 3 of 6)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
J	2.661	4.1	0.0321	0.0306	6230	0.176
	2.672	4	0.0386	0.0378	5181	0.227
	2.689	4.2	0.0306	0.0301	6536	0.248
	2.687	4.0	0.0367	0.0367	5450	0.224
	2.675	4.0	0.0396	0.0396	5050	0.193
Avg	2.677	4.1	0.0355	0.0350	5634	0.214
Std	0.011	0.1	0.0040	0.0043	658	0.029
K	2.627	4.5	0.0400	0.0400	5000	0.248
	2.641	3.9	0.0341	0.0340	5865	0.326
	2.64	3.7	0.0445	0.0444	4494	0.227
	2.634	4.1	0.0395	0.0393	5063	0.218
	2.649	4.0	0.0352	0.0351	5682	0.247
Avg	2.638	4.0	0.0387	0.0386	5168	0.253
Std	0.008	0.3	0.0042	0.0042	554	0.043
L	2.627	3.9	0.0358	0.0358	5587	0.226
	2.645	3.7	0.0431	0.0431	4640	0.136
	2.584	3.7	0.0486	0.0467	4283	0.228
	2.569	3.6	0.0300	0.0280	7143	0.190
Avg	2.606	3.7	0.0394	0.0384	5208	0.195
Std	0.036	0.2	0.0082	0.0083	1278	0.043

(Sheet 4 of 6)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
M	2.606	3.7	0.0371	0.0371	5391	0.248
	2.616	4.4	0.0430	0.0429	4651	0.265
	2.620	4.3	0.0398	0.0398	5025	0.265
Avg	2.614	4.1	0.0400	0.0399	5000	0.259
Std	0.007	0.4	0.0030	0.0029	370	0.10
N	2.669	4.3	0.0361	0.0361	5540	0.159
	2.696	4.3	0.0443	0.0443	4515	0.220
	2.747	4.1	0.0443	0.0441	4515	0.223
	2.704	4.2	0.0385	0.0384	5195	0.250
Avg	2.704	4.2	0.0408	0.0407	4902	0.213
Std	0.032	0.1	0.0042	0.0041	512	0.038
O	2.675	4.1	0.0451	0.0450	4444	0.231
	2.690	3.8	0.0463	0.0463	4320	0.259
	2.691	3.9	0.0441	0.0440	4545	0.282
	2.690	3.8	0.0468	0.0467	4283	0.235
	2.608	3.9	0.0477	0.0477	4193	0.187
	2.549	4.1	0.0417	0.0416	4796	0.234
Avg	2.651	3.9	0.0453	0.0452	4415	0.238
Std	0.059	0.1	0.0022	0.0022	218	0.032

(Sheet 5 of 6)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
P	2.697	3.8	0.0416	0.0416	4808	0.216
	2.630	3.9	0.0420	0.0419	4762	0.217
	2.690	3.9	0.0438	0.0433	4566	0.251
	2.678	3.8	0.0512	0.0512	3906	0.307
Avg	2.674	3.9	0.0447	0.0445	4193	0.248
Std	0.030	0.1	0.0045	0.0045	416	0.043
Q	2.664	3.9	0.0511	0.0510	3914	0.264
	2.657	4.4	0.0469	0.0469	4264	0.222
	2.647	4.0	0.0431	0.0431	4640	0.256
	2.589	3.9	0.0569	0.0569	3515	0.246
Avg	2.639	4.1	0.0495	0.0495	4040	0.247
Std	0.034	0.2	0.0059	0.0059	481	0.018
R	2.517	3.7	0.0833	0.0828	2401	0.375
	2.498	3.5	0.0845	0.0833	2367	0.395
	2.507	3.8	0.0868	0.0868	2304	0.326
Avg	2.507	3.7	0.0849	0.0843	2356	0.365
Std	0.010	0.2	0.0018	0.0022	49	0.036

(Sheet 6 of 6)

Table B2. Confined Repeated Load Deformation Test Results for SBS Modified AC-20 Mixtures

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
A	2.422	4.0	0.0212	0.0212	9434	0.072
	2.428	4.0	0.0227	0.0227	8811	0.063
	2.430	3.9	0.0181	0.0181	11050	0.094
	2.417	3.9	0.0257	0.0254	7782	0.096
Avg	2.424	4.0	0.0219	0.0219	9132	0.081
Std	0.006	0.1	0.0032	0.0030	1369	0.016
C	2.433	4.1	0.0199	0.0199	10050	0.041
	2.425	3.8	0.0201	0.0201	9950	0.076
	2.424	3.8	0.0254	0.0254	7874	0.114
Avg	2.427	3.9	0.0218	0.0218	9174	0.077
Std	0.005	0.2	0.0031	0.0031	1228	0.037
E	2.407	4.1	0.0194	0.0194	10309	0.144
	2.411	4.3	0.0220	0.0219	9091	0.058
	2.416	4.1	0.0253	0.0253	7905	0.072
	2.412	4.2	0.0238	0.0237	8403	0.108
Avg	2.412	4.2	0.0226	0.0226	8850	0.096
Std	0.004	0.1	0.0025	0.0025	1042	0.039

(Sheet 1 of 3)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
I	2.677	3.9	0.0180	0.0180	11111	0.161
	2.667	4.0	0.0207	0.0207	9662	0.168
	2.675	4.1	0.0244	0.0244	8197	0.177
	2.671	4.1	0.0215	0.0215	9302	0.116
Avg	2.673	4.0	0.0212	0.0212	9434	0.156
Std	0.004	0.1	0.0026	0.0026	1203	0.027
M	2.567	3.9	0.0274	0.0274	7299	0.114
	2.583	4.1	0.0433	0.0433	4619	0.179
	2.595	4.0	0.0270	0.0269	7407	0.135
	2.579	4.0	0.0467	0.0467	4283	0.164
Avg	2.581	4.0	0.0361	0.0361	5540	0.148
Std	0.012	0.1	0.0104	0.0104	1682	0.029
O	2.666	4.0	0.0208	0.0207	9615	0.212
	2.692	4.9	0.0173	0.0173	11560	0.132
	2.668	3.9	0.0373	0.0372	5362	0.152
	2.661	4.1	0.0239	0.0239	8368	0.105
	2.671	4.2	0.0300	0.0300	6667	0.182
Avg	2.672	4.2	0.0259	0.0258	7722	0.157
Std	0.012	0.4	0.0079	0.0079	2432	0.042

(Sheet 2 of 3)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
Q	2.634	4.1	0.0435	0.0435	4598	0.153
	2.655	4.2	0.0269	0.0269	7435	0.182
	2.630	4.0	0.0318	0.0318	6289	0.132
Avg	2.640	4.1	0.0341	0.0341	5865	0.156
Std	0.013	0.1	0.0085	0.0085	1427	0.025
R	2.551	4.0	0.0448	0.0441	4464	0.223
	2.519	3.6	0.0439	0.0437	4556	0.189
	2.539	4.0	0.0401	0.0401	4988	0.186
Avg	2.536	3.9	0.0429	0.0426	4662	0.199
Std	0.016	0.2	0.0025	0.0022	280	0.021

(Sheet 3 of 3)

Table B3. Confined Repeated Load Deformation Test Results for LDPE Modified AC-20 Mixtures

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
A	2.450	4.2	0.0198	0.0198	10101	0.093
	2.445	4.3	0.0192	0.0192	10417	0.084
	2.430	4.2	0.0188	0.0188	10638	0.107
Avg	2.442	4.2	0.0193	0.0193	10363	0.095
Std	0.010	0.1	0.0005	0.0005	270	0.012
C	2.419	3.9	0.0211	0.0210	9479	0.068
	2.428	4.1	0.0187	0.0187	10695	0.065
	2.405	3.7	0.0272	0.0272	7353	0.106
Avg	2.417	3.9	0.0223	0.0223	8969	0.080
Std	0.012	0.2	0.0044	0.0044	1692	0.023
E	2.413	4.0	0.0275	0.0275	7273	0.110
	2.412	4.0	0.0293	0.0293	6826	0.117
	2.411	4.0	0.0320	0.0320	6250	0.071
	2.411	4.0	0.0292	0.0291	6849	0.103
Avg	2.412	4.0	0.0295	0.0295	6780	0.100
Std	0.001	0.0	0.0019	0.0019	420	0.020

(Sheet 1 of 3)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
I	2.673	4.0	0.0494	0.0493	4049	0.138
	2.691	4.1	0.0410	0.0409	4878	0.066
	2.691	4.4	0.0270	0.0263	7407	0.231
	2.675	4.4	0.0392	0.0392	5102	0.076
Avg	2.677	4.2	0.0392	0.0389	5102	0.128
Std	0.009	0.2	0.0092	0.0095	1438	0.076
M	2.576	4.0	0.0481	0.0480	4158	0.182
	2.578	3.9	0.0390	0.0390	5128	0.189
	2.597	3.9	0.0364	0.0363	5495	0.184
Avg	2.584	3.9	0.0412	0.0411	4854	0.185
Std	0.012	0.1	0.0061	0.0061	691	0.004
O	2.668	4.2	0.0280	0.0279	7143	0.105
	2.624	3.9	0.0345	0.0345	5797	0.08
	2.662	4.4	0.0352	0.0352	5682	0.079
	2.619	4.2	0.0346	0.0345	5780	0.068
Avg	2.643	4.2	0.0331	0.0330	6042	0.083
Std	0.025	0.2	0.0034	0.0034	697	0.016

(Sheet 2 of 3)

Mix number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
Q	2.669	3.7	0.0429	0.0429	4662	0.138
	2.551	4.1	0.0584	0.0584	3425	0.146
	2.570	4.2	0.0487	0.0487	4107	0.14
Avg	2.597	4.0	0.0500	0.0500	4000	0.141
Std	0.063	0.3	0.0078	0.0078	620	0.004
R	2.504	3.6	0.0867	0.0867	2307	0.268
	2.523	3.9	0.0606	0.0606	3300	0.239
	2.522	3.9	0.0559	0.0559	3578	0.320
	2.535	3.8	0.0764	0.0764	2618	0.401
Avg	2.521	3.8	0.0699	0.0699	2861	0.307
Std	0.013	0.2	0.0142	0.0142	589	0.071

(Sheet 3 of 3)

Table B4. Confined Repeated Load Deformation Test Results for Test Section Items - Lab Compacted

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
1	2.510	4.3	0.0181	0.0181	11050	0.145
	2.510	4.3	0.0208	0.0209	9615	0.149
	2.498	4.3	0.0208	0.0208	9615	0.137
	2.504	4.5	0.0179	0.0178	11173	0.152
Avg	2.506	4.4	0.0194	0.0194	10309	0.146
Std	0.007	0.0	0.0016	0.0016	828	01006
2	2.469	2.4	0.0202	0.0202	9901	0.099
	2.461	2.2	0.0232	0.0230	8621	0.086
	2.471	2.4	0.0221	0.0221	9050	0.079
	2.463	2.0	0.0209	0.0209	9569	0.104
Avg	2.466	2.3	0.0216	0.0216	9254	0.092
Std	0.005	0.1	0.0015	0.0014	651	0.010
3	2.534	4.5	0.0267	0.0267	7491	0.205
	2.629	4.4	0.0353	0.0353	5666	0.127
	2.540	4.6	0.0248	0.0248	8065	0.264
Avg	2.568	4.5	0.0289	0.0289	6920	0.199
Std	0.067	0.1	0.0061	0.0061	1290	0.055

(Sheet 1 of 4)

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
4	2.583	6.6	0.0173	0.0173	11561	0.103
	2.576	6.6	0.0127	0.0127	15748	0.130
	2.577	6.5	0.0236	0.0235	8475	0.064
Avg	2.579	6.6	0.0179	0.0178	11173	0.099
Std	0.005	0.0	0.0033	0.0033	2961	0.019
5	2.463	2.5	0.0193	0.0192	10363	0.104
	2.484	2.2	0.0220	0.0220	9091	0.083
	2.491	2.2	0.0237	0.0237	8439	0.098
Avg	2.479	2.3	0.0217	0.0216	9216	0.095
Std	0.015	0.2	0.0019	0.0020	899	0.015
6	2.631	7.2	0.0294	0.0294	6803	0.061
	2.630	7.2	0.0168	0.0168	11905	0.106
	2.643	7.2	0.0264	0.0264	7576	0.051
	2.629	7.1	0.0266	0.0266	7519	0.111
Avg	2.633	7.2	0.0248	0.0248	8065	0.082
Std	0.007	0.0	0.0066	0.0066	2750	0.029

(Sheet 2 of 4)

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
7	2.548	5.1	0.0219	0.0219	9132	0.051
	2.546	5.1	0.0159	0.0159	12579	0.072
	2.547	5.1	0.0196	0.0196	10204	0.050
	2.555	5.3	0.0206	0.0206	9709	0.043
Avg	2.549	5.2	0.0195	0.0195	10256	0.054
Std	0.004	0.1	0.0026	0.0026	1513	0.012
8	2.593	3.5	0.0226	0.0225	8850	0.172
	2.586	3.3	0.0213	0.0212	9390	0.220
	2.586	3.5	0.0216	0.0216	9259	0.120
	2.589	3.5	0.175	0.175	11429	0.069
Avg	2.589	3.5	0.0208	0.0207	9615	0.145
Std	0.003	0.1	0.0022	0.0022	1154	0.065
9	2.574	3.0	0.0208	0.0208	9615	0.154
	2.578	3.0	0.0278	0.0278	7194	0.121
	2.574	3.0	0.0151	0.0151	13245	0.197
Avg	2.575	3.0	0.0212	0.0212	9434	0.157
Std	0.002	0.0	0.0064	0.0064	3046	0.038

(Sheet 3 of 4)

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
10	2.563	2.2	0.0331	0.0326	6042	0.235
	2.563	2.4	0.0437	0.0437	4577	0.389
	2.553	2.4	0.0421	0.0421	4751	0.397
	2.563	2.4	0.0345	0.0345	5797	0.296
Avg	2.561	2.4	0.0384	0.0383	5208	0.329
Std	0.005	0.1	0.0053	0.0054	735	0.078

(Sheet 4 of 4)

Table B5. Confined Repeated Load Deformation Test Results for Test Section Items - Field Compaction

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
1	2.645	10.3	0.0340	0.0340	5882	0.148
	3.007	9.6	0.0249	0.0248	8032	0.137
	3.037	8.7	0.0221	0.0222	9050	0.079
Avg	2.896	9.5	0.0270	0.0270	7407	0.121
Std	0.218	0.8	0.0062	0.0062	1617	0.037
2	2.582	7.4	0.0489	0.0489	4090	0.140
	2.808	7.4	0.0378	0.0378	5291	0.081
	2.545	7.6	0.0335	0.0335	5970	0.148
Avg	2.645	7.5	0.0401	0.0401	4988	0.123
Std	0.142	0.1	0.0079	0.0079	952	0.037
3	2.240	12.2	0.0848	0.0848	2358	0.155
	2.534	9.6	0.0532	0.0531	3759	0.167
	2.674	7.8	0.0371	0.0371	5391	0.193
Avg	2.483	9.9	0.0584	0.0583	3425	0.172
StD	0.222	2.2	0.0243	0.0243	1518	0.019

(Sheet 1 of 3)

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
4	2.892	6.9	0.0241	0.0241	8299	0.153
	2.509	7.9	0.0271	0.0271	7380	0.099
	2.315	7.5	0.0235	0.0234	8511	0.116
Avg	2.572	7.4	0.0249	0.0249	8032	0.123
Std	0.294	0.5	0.0019	0.0020	601	0.028
5	2.714	6.3	0.0417	0.0417	4796	0.128
	2.509	5.4	0.0343	0.0343	5831	0.131
	2.892	5.4	0.0186	0.0186	10753	0.118
Avg	2.705	5.7	0.0315	0.0315	6349	0.126
Std	0.192	0.5	0.0118	0.0118	3183	0.007
6	2.705	8.8	0.0329	0.0329	6079	0.094
	2.738	9.4	0.0565	0.0565	3540	0.078
	2.550	9.9	0.0644	0.0644	3106	0.103
Avg	2.664	9.4	0.0513	0.0513	3899	0.092
Std	0.100	0.6	0.0164	0.0164	1606	0.013
7	2.657	8.2	0.0450	0.0450	4444	0.071
	2.626	7.8	0.0318	0.0318	6289	0.110
	2.938	7.5	0.0450	0.0450	4444	0.137
Avg	2.740	7.8	0.0406	0.0406	4926	0.106
Std	0.172	0.4	0.0076	0.0076	1065	0.033

(Sheet 2 of 3)

Item number	Thickness (in.)	Voids total mix (%)	Total strain (in/in.)	Permanent strain (in/in.)	Creep modulus based on deviator stress (psi)	Slope of creep curve (M)
8	2.860	5.1	0.0652	0.0652	3067	0.156
	2.686	5.9	failed	failed	failed	failed
	2.417	7.8	0.0580	0.0580	3448	0.09
Avg	2.654	6.3	0.0616	0.0616	3247	0.123
9	2.736	8.7	0.0311	0.0310	6431	0.184
	2.695	8.6	0.0328	0.0328	6098	0.132
	2.828	7.5	0.0926	0.0925	2160	0.091
Avg	2.753	8.3	0.0522	0.0521	3831	0.136
Std	0.068	0.7	0.0350	0.0350	2376	0.047
10	2.067	7.8	0.0607	0.0607	3295	0.149
	2.314	7.1	0.0434	0.0434	4608	0.206
	2.567	7.5	0.0374	0.0373	5348	0.196
Avg	2.316	7.5	0.0472	0.0471	4237	0.184
Std	0.250	0.4	0.0121	0.0121	1040	0.030

(Sheet 3 of 3)

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In recent years, the incidence of premature rutting in hot mix asphalt (HMA) pavements has increased. This deformation usually develops in the wheelpaths under channelized traffic in the top 3 to 4 in. of the HMA pavement. The primary cause of this premature rutting has been higher traffic volumes, increased loads and tire pressures, and lower quality HMA mixtures. This investigation focused on permanent deformation produced by plastic flow and densification of the HMA layers.

Approximately 85 percent of the total volume of HMA mixtures is aggregate, and the performance of HMA mixtures is greatly influenced by aggregate properties. This study was conducted to evaluate the influence of these properties on permanent deformation characteristics of HMA mixtures. The analysis consisted of correlating aggregate properties with HMA mixture properties and the rutting potential of HMA pavements.

The research study consisted of a literature review, laboratory evaluation, and field evaluation. The laboratory evaluation consisted of aggregate characterization tests and HMA mixture tests. The aggregate characterization tests included Particle Index, National Aggregate Association (NAA), and Modified NAA particle shape and texture, unit weight and voids in aggregates, and direct shear tests. The HMA mixtures were evaluated with Marshall properties, Gyratory Testing Machine,

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UNCLASSIFIED	UNCLASSIFIED		

13. (Concluded).

indirect tensile tests, direct shear tests, and confined repeated load deformation tests. The field evaluation included construction of 10 test items, trafficking with a load cart simulating aircraft loads and tire pressures, and evaluating performance with rut depth measurements.

The findings of the laboratory evaluation indicated that the Particle Index, NAA and modified NAA particle shape and texture, unit weight and voids in aggregate tests, and the Gyratory Elasto-Plastic index value could be used to accurately characterize the shape and texture of aggregates. The laboratory evaluation also indicated that the confined repeated load permanent deformation test could produce a significant difference in rutting potential for HMA mixtures with different percentages of crushed aggregate.

The evaluation and analysis of the field test items indicated that no single aggregate or HMA mixture property could predict rutting and that HMA rutting was a complex process. Surprisingly, the Marshall stability/flow ratio had the best individual correlation with rutting in HMA pavements of all mixture properties.